DEVELOPMENT AND CHARACTERIZATION OF METAL MATRIX COMPOSITE USING RED MUD AN INDUSTRIAL WASTE FOR WEAR RESISTANT APPLICATIONS

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF

Doctor of Philosophy

in

Mechanical Engineering

By

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CERTIFICATE

This is to certify that the thesis entitled "**Development and Characterization of Metal Matrix Composite Using Red Mud an Industrial Waste for Wear Resistant Applications"** submitted to the National Institute of Technology, Rourkela (Deemed University) by **Naresh Prasad**, Roll No. 50203003 for the award of the Degree of Doctor of Philosophy in Mechanical Engineering is a record of bonafide research work carried out by him under my supervision and guidance. The results presented in this thesis has not been, to the best of my knowledge, submitted to any other University or Institute for the award of any degree or diploma.

The thesis, in my opinion, has reached the standards fulfilling the requirement for the award of the degree of **Doctor of Philosophy** in accordance with regulations of the Institute.

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(Naresh Prasad)

ABSTRACT

Red mud emerges as the major waste material during production of alumina from bauxite by the Bayer's process. It comprises of oxides of iron, titanium, aluminum and silica along with some other minor constituents. Based on economics as well as environmental related issues, enormous efforts have been directed worldwide towards red mud management issues i.e. of utilization, storage and disposal. Different avenues of red mud utilization are more or less known but none of them have so far proved to be economically viable or commercially feasible.

It is generally agreed that resistance to wear of MMCs is created by reinforcement and also the wear properties are improved remarkably by introducing hard intermetallic compound into the aluminium matrix. The reinforcing materials are generally SiC, Al_2O_3, TiB_2 etc and are costly. The present research work has been undertaken with an objective to explore the use of red mud as a reinforcing material as a low cost option. This is due to the fact that red mud alone contains all these reinforcement elements and is plentifully available.

Experiments have been conducted under laboratory condition to assess the wear characteristics of the aluminium red mud composite under different working conditions in pure sliding mode on a pin-on-disc machine. This has been possible by fabricating the samples through usual stir casting technique. To enhance the wear properties, the samples were also subjected to heat treatment. The worn surfaces of the wear out samples were studied under optical microscope to get an idea about the effect of particulate reinforcement on the wear behavior of the composite.

Dispersion of red mud particles in aluminium matrix improves the hardness of the matrix material and also the wear behavior of the composite. Wear resistance of the composite can be improved by heat treatment and proper choice of cooling media. A prediction model using artificial neural networks (ANN) is also employed to simulate the

property parameters correlation and a fairly good agreement in the experimental and predicted value is obtained.

There are other fabrication techniques available where the volume fraction of reinforcements could be increased and are likely to vary the wear performances of the composite. This work can be further extended to those techniques. However these results can act as a starting point for both industrial designers and researchers to design and develop MMC components using this industrial waste for applications in wear environment.

The whole dissertation has been divided into six chapters to put the analysis independent of each other as far as possible. The major work on wear characteristics and validation of results through Artificial Neural Network (ANN) techniques are given in chapter 3, 4, and 5 respectively.

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NOMENCLATURE

A	Air cooling
E	Young's modulus
E_a	Experimental values for air cooling
E_w	Experimental values for water quenching
E_{w15}	Experimental values for water quenching at 15^0C
E_{w5}	Experimental values for water quenching at 5^0C
F_f	Average frictional force
F_n	Normal load
f	Volume fraction
H	Vickers hardness
K	Wear coefficient
L	Load
m_1	Initial mass
m_2	Final mass
Δm	Difference in mass
P_a	Predicted values for air cooling
P_w	Predicted values for water quenching
P_{w15}	Predicted values for water quenching at 15^0C
P_{w5}	Predicted values for water quenching at 5^0C
rpm	Revolution per minute
R.D.	Rolling / Sliding distance

t	Time
V	Wear volume
V_s	Sliding velocity
W_r	Wear rate
W	Water quenching
WHT	Without heat treatment
Ws	Specific wear rate
Wv	Volumetric wear rate
μ	Co-efficient of friction
ρ	Density

*****

CHAPTER – 1

1.1 BACKGROUND

History is often marked by the materials and technology that reflect human capability and understanding. Many times scales begins with the stone age, which led to the Bronze, Iron, Steel, Aluminium and Alloy ages as improvements in refining, smelting took place and science made all these possible to move towards finding more advance materials possible.

Progress in the development of advanced composites from the days of E glass / Phenolic radome structures of the early 1940's to the graphite/ polymide composites used in the space shuttle orbiter-is spectacular. The recognition of the potential weight savings that can be achieved by using the advanced composites, which in turn means reduced cost and greater efficiency, was responsible for this growth in the technology of reinforcements, matrices and fabrication of composites. If the first two decades saw the improvements in the fabrication method, systematic study of properties and fracture mechanics was at the focal point in the 60's. Since than there has been an ever-increasing demand for newer, stronger, stiffer and yet lighter-weight materials in fields such as aerospace, transportation, automobile and construction sectors. Composite materials are emerging chiefly in response to unprecedented demands from technology due to rapidly advancing activities in aircrafts, aerospace and automotive industries. These materials have low specific gravity that makes their properties particularly superior in strength and modulus to many traditional engineering materials such as metals. As a result of intensive studies into the fundamental nature of materials and better understanding of their structure property relationship, it has become possible to develop new composite materials with improved physical and mechanical properties. These new materials include high performance composites such as Polymer matrix composites [1, 2], Ceramic matrix composites [3, 4] and Metal matrix composites [5] etc. Continuous advancements have led to the use of composite materials in more and more diversified applications. The importance of composites as engineering materials is reflected by the fact that out of over 1600 engineering materials available in the market today more than 200 are composite [6].

1.2 COMPOSITES

1.2.1 Why a composite?

Over the last thirty years composite materials, plastics and ceramics have been the dominant emerging materials. The volume and number of applications of composite materials have grown steadily, penetrating and conquering new markets relentlessly. Modern composite materials constitute a significant proportion of the engineered materials market ranging from everyday products to sophisticated niche applications.

While composites have already proven their worth as weight-saving materials, the current challenge is to make them cost effective. The efforts to produce economically attractive composite components have resulted in several innovative manufacturing techniques currently being used in the composites industry. It is obvious, especially for composites, that the improvement in manufacturing technology alone is not enough to overcome the cost hurdle. It is essential that there be an integrated effort in design, material, process, tooling, quality assurance, manufacturing, and even program management for composites to become competitive with metals.

The composites industry has begun to recognize that the commercial applications of composites promise to offer much larger business opportunities than the aerospace sector due to the sheer size of transportation industry. Thus the shift of composite applications from aircraft to other commercial uses has become prominent in recent years.

Increasingly enabled by the introduction of newer polymer resin matrix materials and high performance reinforcement fibres of glass, carbon and aramid, the penetration of these advanced materials has witnessed a steady expansion in uses and volume. The increased volume has resulted in an expected reduction in costs. High performance FRP can now be found in such diverse applications as composite armoring designed to resist explosive impacts, fuel cylinders for natural gas vehicles, windmill blades, industrial drive shafts, support beams of highway bridges and even paper making rollers. For certain applications, the use of composites rather than metals has in fact resulted in savings of both cost and weight. Some examples are cascades for engines, curved fairing and fillets, replacements for welded metallic parts, cylinders, tubes, ducts, blade containment bands etc.

Further, the need of composite for lighter construction materials and more seismic resistant structures has placed high emphasis on the use of new and advanced materials that not only decreases dead weight but also absorbs the shock & vibration through tailored microstructures. Composites are now extensively being used for rehabilitation/ strengthening of pre-existing structures that have to be retrofitted to make them seismic resistant, or to repair damage caused by seismic activity.

Unlike conventional materials (e.g., steel), the properties of the composite material can be designed considering the structural aspects. The design of a structural component using composites involves both material and structural design. Composite properties (e.g. stiffness, thermal expansion etc.) can be varied continuously over a broad range of values under the control of the designer. Careful selection of reinforcement type enables finished product characteristics to be tailored to almost any specific engineering requirement.

Whilst the use of composites will be a clear choice in many instances, material selection in others will depend on factors such as working lifetime requirements, number of items to be produced (run length), complexity of product shape, possible savings in assembly costs and on the experience & skills the designer in tapping the optimum potential of composites. In some instances, best results may be achieved through the use of composites in conjunction with traditional materials.

1.2.2 What is a composite?

A typical composite material is a system of materials composing of two or more materials (mixed and bonded) on a macroscopic scale.

Generally, a composite material is composed of reinforcement (fibers, particles, flakes, and/or fillers) embedded in a matrix (polymers, metals, or ceramics). The matrix holds the reinforcement to form the desired shape while the reinforcement improves the overall mechanical properties of the matrix. When designed properly, the new combined material exhibits better strength than would each individual material.

As defined by Jartiz, [7] Composites are multifunctional material systems that provide characteristics not obtainable from any discrete material. They are cohesive structures made by physically combining two or more compatible materials, different in composition and characteristics and sometimes in form.

Kelly [8] very clearly stresses that the composites should not be regarded simple as a combination of two materials. In the broader significance; the combination has its own distinctive properties. In terms of strength or resistance to heat or some other desirable quality, it is better than either of the components alone or radically different from either of them.

Berghezan [9] defines as "The composites are compound materials which differ from alloys by the fact that the individual components retain their characteristics but are so incorporated into the composite as to take advantage only of their attributes and not of their shortcomings", in order to obtain an improved material

Van Suchetclan [10] explains composite materials as heterogeneous materials consisting of two or more solid phases, which are in intimate contact with each other on a microscopic scale. They can be also considered as homogeneous materials on a microscopic scale in the sense that any portion of it will have the same physical property.

1.2.3 Characteristics of the Composites

Composites consist of one or more discontinuous phases embedded in a continuous phase. The discontinuous phase is usually harder and stronger than the continuous phase and is called the 'reinforcement' or 'reinforcing material', whereas the continuous phase is termed as the ' matrix'.

Properties of composites are strongly dependent on the properties of their constituent materials, their distribution and the interaction among them. The composite properties may be the volume fraction sum of the properties of the constituents or the constituents may interact in a synergistic way resulting in improved or better properties. Apart from the nature of the constituent materials, the geometry of the reinforcement (shape, size and size distribution) influences the properties of the composite to a great extent. The concentration distribution and orientation of the reinforcement also affect the properties.

The shape of the discontinuous phase (which may by spherical, cylindrical, or rectangular cross-sanctioned prisms or platelets), the size and size distribution (which controls the texture of the material) and volume fraction determine the interfacial area, which plays an important role in determining the extent of the interaction between the reinforcement and the matrix.

Concentration, usually measured as volume or weight fraction, determines the contribution of a single constituent to the overall properties of the composites. It is not only the single most important parameter influencing the properties of the composites, but also an easily controllable manufacturing variable used to alter its properties.

The orientation of the reinforcement affects the isotropy of the system.

1.2.4 Classification of Composites

Composite materials can be classified in different ways [11]. Classification based on the geometry of a representative unit of reinforcement is convenient since it is the geometry of the reinforcement which is responsible for the mechanical properties and high performance of the composites. A typical classification is presented in table1.1. The two broad classes of composites are (1) Particulate composites and (2) fibrous composites.

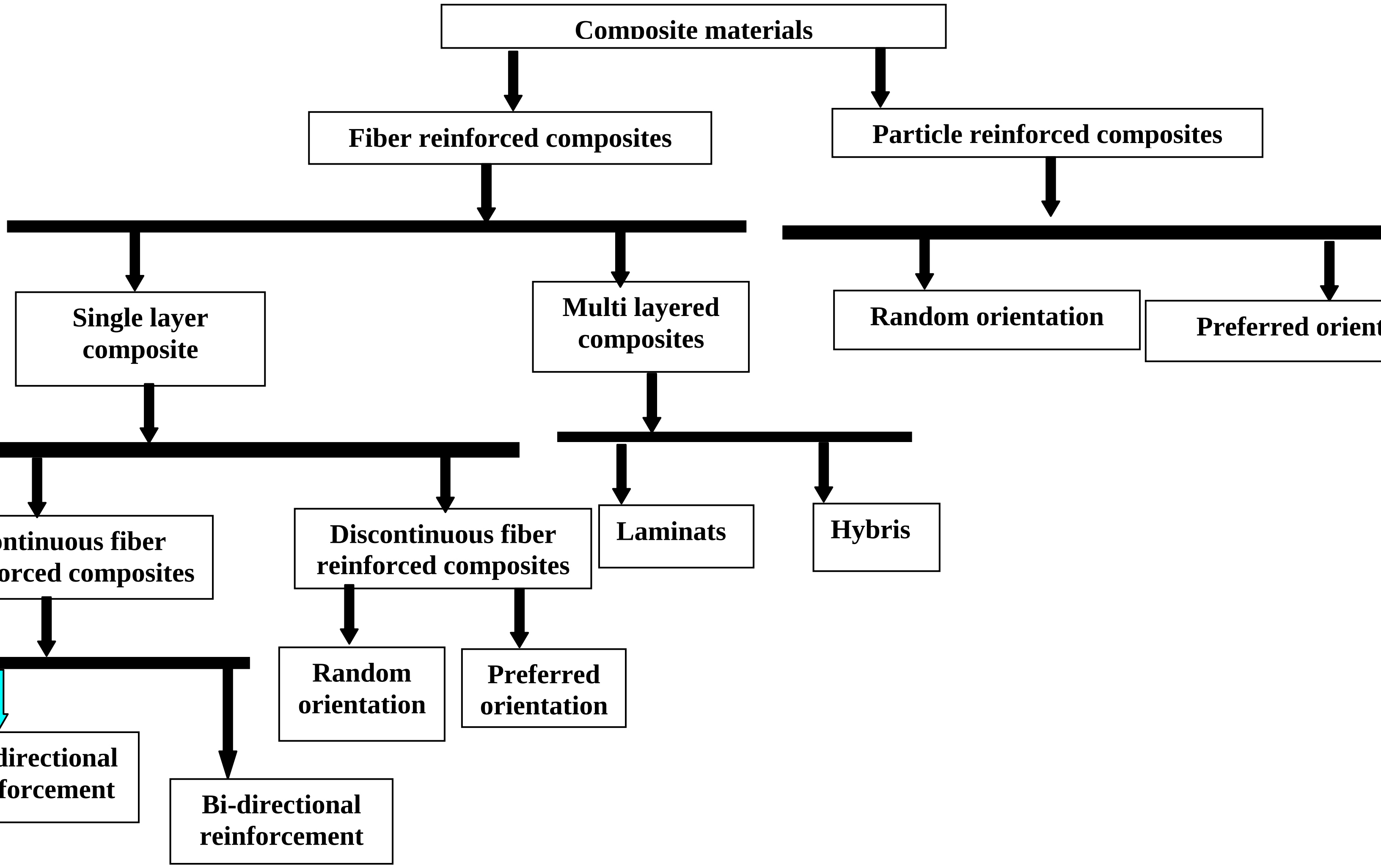

Table: 1 .1 Classification of composites

1.2.4.1 Particulate Composites

As the name itself indicates, the reinforcement is of particle nature (platelets are also included in this class). It may be spherical, cubic, tetragonal, a platelet, or of other regular or irregular shape, but it is approximately equiaxed. In general, particles are not very effective in improving fracture resistance but they enhance the stiffness of the composite to a limited extent. Particle fillers are widely used to improve the properties of matrix materials such as to modify the thermal and electrical conductivities, improve performance at elevated temperatures, reduce friction, increase wear and abrasion resistance, improve machinability, increase surface hardness and reduce shrinkage.

1.2.4.2 Fibrous composites

A fiber is characterized by its length being much greater compared to its cross-sectional dimensions. The dimensions of the reinforcement determine its capability of contributing its properties to the composite. Fibers are very effective in improving the fracture resistance of the matrix since a reinforcement having a long dimension discourages the growth of incipient cracks normal to the reinforcement that might other wise lead to failure, particularly with brittle matrices.

Man-made filaments or fibers of non polymeric materials exhibit much higher strength along their length since large flaws, which may be present in the bulk material, are minimized because of the small cross-sectional dimensions of the fibre. In the case of polymeric materials, orientation of the molecular structure is responsible for high strength and stiffness.

Fibers, because of their small cross- sectional dimensions, are not directly usable in engineering applications. They are, therefore, embedded in matrix materials to form fibrous composites. The matrix serves to bind the fibers together, transfer loads to the fibers, and protect them against environmental attack and damage due to handling. In discontinuous fibre reinforced composites, the load transfer function of the matrix is more critical than in continuous fibre composites.

1.3 COMPONENTS OF A COMPOSITE MATERIAL

In its most basic form a composite material is one, which is composed of at least two elements working together to produce material properties that are different to the properties of those elements on their own. In practice, most composites consist of a bulk material (the ‘matrix’), and a reinforcement of some kind, added primarily to increase the strength and stiffness of the matrix.

1.3.1 Role of matrix in a composite

Many materials when they are in a fibrous form exhibit very good strength property but to achieve these properties the fibres should be bonded by a suitable matrix. The matrix isolates the fibres from one another in order to prevent abrasion and formation of new surface flaws and acts as a bridge to hold the fibres in place. A good matrix should possess ability to deform easily under applied load, transfer the load onto the fibres and evenly distributive stress concentration.

A study of the nature of bonding forces in laminates [12] indicates that upon initial loading there is a tendency for the adhesive bond between the reinforcement and the matrix to be broken. The frictional forces between them account for the high strength properties of the laminates.

1.3.2 Materials used as matrices in composites

In its most basic form a composite material is one, which is composed of at least two elements working together to produce material properties that are different to the properties of those elements on their own. In practice, most composites consist of a bulk material (the matrix) and a reinforcement of some kind, added primarily to increase the strength and stiffness of the matrix.

(a) BULK PHASES

(1) Metal Matrices

Metal matrix composites possess some attractive properties, when compared with organic matrices. These include (i) strength retention at higher temperatures, (ii) higher transverse strength, (iii) better electrical conductivity, (iv) superior thermal conductivity, (v) higher erosion resistance etc. However, the major disadvantage of metal matrix composites is their higher densities and consequently lower specific mechanical properties compared to polymer matrix composites. Another notable difficulty is the high-energy requirement for fabrication of such composites.

In the aerospace industry interest has been concentrated primarily on fibre reinforced aluminium and titanium. Boron and to a lesser extent silicon carbide (SiC), have been investigated as the reinforcing fibres. Aluminium alloys reinforced with boron have been extensively produced by a variety of methods. Titanium reinforced with SiC, boron (coated with SiC) and even with beryllium, used for compressor blades.

Good elastic modulus properties can be achieved by the unidirectional incorporation of fibres or whiskers in the metal matrix even though the bonding between them may be poor. But, strong metallic matrices rather than weak metal or polymer matrices are essential for good transverse modulus and shear strength.

Carbon/graphite fibres have been used with metal matrices on a laboratory / experimental scale only, because most basic fabrication techniques involve high temperatures which have detrimental effects on the fibre. However, research on these lines is continuing in view of the potential of the composites.

(2) Polymer Matrices

A very large number of polymeric materials, both thermosetting and thermoplastic, are used as matrix materials for the composites. Some of the major advantages and limitations of resin matrices are shown in Table 1.2.

Table 1.2

Advantages and limitations of polymeric matrix materials

Advantages	Limitations
Low densities	Low transverse strength
Good corrosion resistance	Low operational temperature limits
Low thermal conductivities	
Low electrical conductivities	
Transluscence	
Aesthetic Colour effects	

Generally speaking, the resinous binders (polymer matrices) are selected on the basis of adhesive strength, fatigue resistance, heat resistance, chemical and moisture resistance etc. The resin must have mechanical strength commensurate with that of the reinforcement. It must be easy to use in the fabrication process selected and also stand up to the service conditions. Apart from these properties, the resin matrix must be capable of wetting and penetrating into the bundles of fibres which provide the reinforcement, replacing the dead air spaces therein and offering those physical characteristics capable of enhancing the performance of fibres.

Shear, chemical and electrical properties of a composite depend primarily on the resin. Again, it is the nature of the resin that will determine the usefulness of the laminates in the presence of a corroding environment.

Generally Speaking, it can be assumed that in composites, even if the volume fraction of the fibre is high (of the order of 0.7), the reinforcement is completely covered by the matrix material; and when the composite is exposed to higher temperatures it is the matrix, which should withstand the hostile environment. Of course, the strength properties of the composite also show deterioration, which may be due to the influence of the temperature on the interfacial bond. Thus, the high temperature resistant properties of the composites are directly related more to the matrix, rather than to the reinforcement. The search for polymers which can withstand high temperatures has pushed the upper limit of the service temperatures to about 300-350^{0}C. This range of operational temperatures can be withstood by polyimides, which are the state-of-the-art high temperature polymers for the present.

Table 1.3 and 1.4 indicate the approximate service temperature ranges for the resins and composites [13, 14]. It should be remembered that there is no place for compromise as to the nature of the matrix material, particularly when it comes to the application temperature of the composite. If the application temperature exceeds 300-350^{0}C metal matrix appears to be the only alternative, at least for the present.

Table 1.3

Application temperatures of some matrix material

Matrix material	Limit of long term exposure, ^{0}C	Limit of short term exposure, ^{0}C
Unsaturated polyesters	70	100
Epoxies	125	200
Phenolics	250	1600
Polyimides	315	400
Aluminium	300	350

Table - 1.4

Trends for temperature application of heat resistant composites

Fibre reinforced Composite	Maximum service temperature, ^0C	Specific weight gm/cm^3
Carbon / Epoxy	180	1.4
Boron/Epoxy	180	2.1
Borsic / Aluminium	310	2.8
Carbon/Polyimide	310	1.4
Boron/Polyimide	310	2.1
Carbon/Polyaminoxaline	350	1.4
Carbon/Polybenzthiazole	400	14
Borsic/Titanium	540	3.6
Carbon/Nickel	930	5.3
Whisker/Metals	1800	2.8-5.6

(3) Ceramic Matrices

Ceramic fibres, such as alumina and SiC (Silicon Carbide) are advantageous in very high temperature applications, and also where environment attack is an issue. Since ceramics have poor properties in tension and shear, most applications as reinforcement are in the particulate form (e.g. zinc and calcium phosphate). Ceramic Matrix Composites (CMCs) used in very high temperature environments, these materials use a ceramic as the matrix and reinforce it with short fibres, or whiskers such as those made from silicon carbide and boron nitride.

(b) REINFORCEMENT

The role of the reinforcement in a composite material is fundamentally one of increasing the mechanical properties of the neat resin system. All of the different fibres used in composites have different properties and so affect the properties of the composite in different ways. For most of the applications, the fibres need to be arranged into some form of sheet, known as a fabric, to make handling possible. Different ways for assembling fibres into sheets and the variety of fibre orientations possible to achieve different characteristics.

(c) INTERFACE

It has characteristics that are not depicted by any of the component in isolation. The interface is a bounding surface or zone where a discontinuity occurs, whether physical, mechanical, chemical etc. The matrix material must "wet" the fibre. Coupling agents are frequently used to improve wettability. Well "wetted" fibres increase the interface surfaces area. To obtain desirable properties in a composite, the applied load should be effectively transferred from the matrix to the fibres via the interface. This means that the interface must be large and exhibit strong adhesion between fibres and matrix. Failure at the interface (called debonding) may or may not be desirable.

1.4 METAL MATRIX COMPOSITE

Metal matrix composites in general, consist of at least two components, one is the metal matrix and the second component is reinforcement. The matrix is defined as a metal in all cases, but a pure metal is rarely used as the matrix. It is generally an alloy. In the productivity of the composite the matrix and the reinforcement are mixed together.

In recent years, the development of metal matrix composite (MMCs) has been receiving worldwide attention on account of their superior strength and stiffness in addition to high wear resistance and creep resistance comparison to their corresponding wrought alloys. The ductile matrix permits the blunting of cracks and stress concentrations by plastic deformation and provides a material with improved fracture toughness.

Cast composites, where the volume and shape of phases is governed by phase diagrams, i.e. Cast iron and Aluminium-silicon alloys have been produced by foundries for a long time. The modern composites differ in the sense that any selected volume, shape and size of reinforcement can be introduced into the matrix. The modern composites are non-equilibrium mixtures of metals and ceramics where there are no thermodynamic restrictions on the relative volume percentages, shapes and size of ceramic phases [15].

The high toughness and impact strength of metals and alloys such as aluminum, titanium, magnesium and nickel-chromium alloys which undergo plastic deformation under impact is of interest in many dynamic structural applications of metallic composites. These materials have also been strengthened considerably by means of various strengthened principles (like grain boundary strengthening, cold working, solid solution strengthening, etc.) to improve their properties. But these approaches are often found to affect the toughness and durability at elevated temperatures and/or under dynamic service conditions. One of the important objectives of metal matrix composites, therefore, is to develop a material with a judicious combination of toughness and stiffness so as to decrease the sensitivity to cracks and flaws and at the same time increase the static and dynamic properties.

This necessity eventually leads to the efficient reinforcement of metals and metal alloys by uni or multidirectional implantation of whiskers or continuous fibers. The reinforcement effect occurs due to the extraordinary high strength of whiskers and fibers with diameters below a few micrometers. Thus, the field of Metal Matrix Composite (MMCs) began in the mid of 1960's with the realization that whisker reinforced MMCs can be competitive with continuous fiber reinforced composites [16], from the standpoint of mechanical properties [17].

The complex fabrication routes, limited fabricability [17, 18] and the small difference in property enhancement between whisker and particulate reinforcement [19] and moreover, the health hazards associated with handling SiC whiskers [20, 21] have shifted the emphasis recently more towards particulate or chopped fibers rather than whisker reinforcement of metals, especially aluminium, because of its light weight and good wettability with silicon carbide [22]. The important shift in metal matrix composite technology began in the mid 80's with more and more discontinuous reinforcement taking the place of continuous reinforcement such as carbides, nitrides, oxides and elemental materials like carbon and silicon.

While discontinuous whisker reinforced MMCs are still under development for aerospace applications, automotive components fabricated from particulate and discontinuous fiber reinforced MMCs, which exhibit essentially isotropic properties, are already in mass production, led by the introduction of diesel piston by Toyota in 1983 followed more recently by engine and cylinder blocks from Honda [23,24].

The present trend, therefore, seems to be towards the development of discontinuously reinforced metal matrix composites which are gaining widespread acceptance primarily because they have recently become available at a relatively low cost compared to uni-and multi-directional continuous fiber reinforced MMCs and the availability of standard or near standard metal working methods which can be utilized to form these MMCs [25]. Discontinuously reinforced aluminium (DRA) composites composed of high strength aluminum and its alloys reinforced with silicon carbide particulates or whiskers are subclass of MMCs. The combination of properties and fabricability of aluminium metal matrix composites makes them attractive candidates for many structural components requiring high-stiffness, high strength and low weight [26].

Now a day's, research all over the globe is focusing mainly on Aluminium [27] because of its unique combination of good corrosion resistance, low density and excellent mechanical properties. The unique thermal properties of Aluminium composites such as metallic conductivity with coefficient of expansion that can be tailored down to zero, add to their prospects in aerospace and avionics.

Thus, entire families of light weight composites, though considered impossible just a few years ago, are either available now or hovering on the brink of commercialization. For example, a series of Aluminium matrix composites reinforced with silicon carbide particulates have been developed by Duralcan USA, Div. Alcan Aluminium corp., San Diego, California [28]. A high temperature creep resistant titanium alloys has been developed as matrix material for the National Aerospace plant by Timet for McDonnell Douglas. Titanium alloy Ti-6Al-4V, reinforced with continuous silicon carbide filaments, is hot isostatically, pressed by Textron for turbine engine shafts [29]. CERAMTEC AG (Germany) is currently utilizing matrix material for MMC products are Aluminium and specially the Al Si_9Cu_3 standard alloy. Apart from being fairly inexpensive in comparison with other light metals (e.g., magnesium and titanium), it has delivered outstanding results in many automotive and aerospace applications and is noted for its uncomplicated processing properties. In practice, the matrix may be constructed of almost any other light alloy or non-ferrous metal, particularly magnesium. They are also developing new ceramic cutting tools, and also superior material for cylinder linings.

Titanium [30] has been used in aero engines mainly for compressor blades and discs due to its higher elevated temperature resistance property. Magnesium is the potential material to fabricate composite for making reciprocating components in motors and for pistons, gudgeon pins, and spring caps [31]. It is also used in aerospace due to its low coefficient of thermal expansion and high stiffness properties combined with low density. The choice of Silicon Carbide as the reinforcement in Aluminum composite is primarily meant to use the composite in missile guidance system replacing certain beryllium components because structural performance is better with out special handling in fabrication demanded by latter’s toxicity [32, 33]. Recently Aluminum- lithium alloy has been attracting the attention of researches due to it’s good wettability characteristics [34].

Successful development and deployment of metal matrix composites are critical to reaching the goals of many advanced aerospace propulsion and power development programs. The specific space propulsion and power applications require high-temperature, high thermal conductivity and high strength materials. Metal matrix composites either fulfill or have the potential of full filling these requirements [35]. Metal matrix composites also offer considerable promise to help automotive engineers meet the challenges of current and future demands [26].

It is thus evident from literature that we can successfully reinforce the SiC, Al_2O_3, TiB_2, boron and graphite in the Aluminum matrix alloy. The reinforced Aluminum matrix alloys have made significant strides from laboratory towards commercialization. But the factors understanding that influence the physical and mechanical properties of these materials is really a challenge [36] because they are sensitive to the type and nature of reinforcement, the mode of manufacture and the details of fabrication processing of the composite after initial manufacture.

Aluminum based alloys are widely used in applications where weight savings are important. However the relatively poor wear resistance of Aluminum alloys has limited their use in certain high friction environments. Literature available on the subject reveals that most of the studies have been carried out to evaluate the wear behavior of Aluminum based particulate or whisker reinforced composites [37-40].

It is generally agreed that the resistance to wear of MMCs is created by reinforcement and higher the volume fraction of particles the better the resistance will be [41-43] however there is an optimum value of the reinforcement which gives maximum wear resistance to the material.

The principle tribological parameters that control the friction and wear performances of reinforced aluminum composite can be classified into two categories. One is mechanical & physical factors and the other are material factors [44]. The mechanical & physical factors has been identified as sliding velocity and normal load, where as, with regards to the material factors they are volume fraction and type of reinforcements. The volume fraction reinforcement has the strongest effect on the wear resistance and this has been studied by many researchers [45-54]. Lot of research has been carried out to prepare MMCs by different type of reinforcements [53-56]. The out come of all these findings is that wear properties are improved remarkably by introducing hard intermetallic compound in to the aluminium matrix.

1.5 NEED FOR THE REINFORCEMENT OF RED MUD INTO ALUMINIUM MATRIX

To obtain Optimum performance from composite materials there is an advantage to selecting the shape and size of the reinforcement material to fit the application. It is apparent that different material types and shapes will have advantages in different matrices. For instance, silicon carbide whiskers have been particularly effective in toughening Al_2O_3 and Si_3N_4 . Both silicon carbide whiskers and silicon carbide grit have been effective in increasing the modulus of aluminium alloys [57]. It is, however, apparent from the literature that particulates offer greater flexibility in tailor making the properties of interest. Thus researchers have worked out separately to reinforce SiC, Al_2O_3 (i.e. carbides, Nitrides and oxides) TiB_2, Boron and Graphite in to the Aluminium matrix to achieve different properties and are expensive.

The ever-increasing demand for low cost reinforcement stimulated the interest towards production and utilization of red mud (an industrial waste from Bayer's process) that contains major elements like Al_2O_3, Fe_2O_3, TiO_2, and Na_2O for preparation of a metal matrix composite for wear resistant application.

1.6 RED MUD

Red mud is the caustic insoluble waste residue generated by alumina production from bauxite by the Bayer's process at an estimated annual rate of 66 and 1.7 million tons, respectively, in the World and India. It is estimated that two tons of alumina used to produce one ton of Aluminium and 58% of alumina and 42% of red mud come out from one ton of bauxite approximately. Under normal conditions, when one ton of alumina is produced nearly a ton of red mud is generated as a waste. In terms of metal production the ratio of aluminium to red mud is 1:2. This waste material has been accumulating at an increasing rate through out the world.

The disposal/utilization of red mud have been an acute problem and a clear-cut solution is not available till date. Different avenues of red mud utilization are more or less known but none of them have so far proved to be economically viable or commercially feasible [58]. However, a survey of literature on utilization of red mud published so far [59-72], it is revealed that use of red mud is restricted only for recovery of some metal values like Titanium, Vanadium and Zinc; making of ceramics etc. It has also been used for making cement, bricks, pigments and glazed sewer pipes etc. Research and development work on red mud utilization that are under process in India are shown in table 1.5. Going through the available information on the utilization of red mud, it is seen that use of red mud as reinforcement material for preparation of MMC has not been explored till date.

Table - 1.5

Research and development work on red mud utilization in India [58].

Organization	Investigation
1. Madras Aluminium Company	Red mud as a component in cement
2. Central building research institute	Production bricks with red mud and clay with equal proportions
3. CECRI, Karaikudi	Materials for primers
4. RRL, Bhubaneswar	Recovery of vanadium, chromium &alumna
5. NEITCO	Manufacture of red mud corrugated sheets.
6. RRL, Bhopal	Utilization of red mud pvc and lab scale product designed as red mud plastic (RMP).
7. Central glass and ceramic research institute	Conversion of red mud to ceramics.
8. NML, Jamshedpur &RRL, BBSR	Recovery of $V_2 O_5$ and Al_2O_3.
9. Metallurgical Dept. B.H.U.	Development of bricks, recovery of titanium and Ferro titanium.
10. Rajasthan Financial Corporation.	Manufacture of pipes and corrugated sheets.
11. NALCO, Ltd	Filler to pvc sheets, pipes and pigment as per ISI norm, patents file.
12. Lotus roofing pvt Ltd.	Corrugated sheets.
13.Dept.of Metallurgy and Material Engg, IIT, Kharagpur.	Conversion of red mud into Ferro alloy and wear resistance cast iron.

The main objective of this work therefore is to prepare a MMC using Red mud as reinforcement and aluminium as matrix material. Out of the available manufacturing procedures we have adopted the usual stir casting technique to prepare the MMC. Different volume fraction of red mud has been mixed with the matrix material and specimens were prepared for wear studies. The wear studies have been carried out using a pin-on-disc wear-testing machine under simulated laboratory conditions. All the experiments have been conducted in dry conditions only, with different variables. The surfaces of the worn out samples have been studied using optical microscope to know the metallurgical effect on the wear rate of different volume fraction of reinforcement.

In the second chapter detailed discussion on selection of aluminium as the matrix material, reinforcement material, overview of the fabrication methods and work related to present investigations available in literatures are presented.

In the third chapter wear characteristics of the composite, with different volume fraction of reinforcement (red mud) has been presented.

Fourth chapter discusses the effect of heat treatment on wear behaviour of composite.

Fifth chapter discusses the Neural Network Approach to predict the wear characteristics. The wear predicted by ANN approach has been presented and compared with the experimental results.

In Sixth chapter conclusions have been drawn from the above studies mentioning scope for future work.

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CHAPTER - 2

LITERATURE SURVEY

2.1 INTRODUCTION

The literature survey is carried out as a part of the thesis work to have an overview of the production processes, properties and wear behaviour of metal matrix composites. Composite structures have shown universally a savings of at least 20% over metal counterparts and a lower operational and maintenance cost [1]. As the data on the service life of composite structures is becoming available, it can be safely said that they are durable, maintain dimensional integrity, resist fatigue loading and are easily maintainable and repairable. Composites will continue to find new applications, but the large scale growth in the marketplace for these materials will require less costly processing methods and the prospect of recycling [73] will have to be solved [74].

It has been reported that the energy consumed when aluminium is recycled is only about 5% of that required in the primary production of aluminium [75]. There are, however, certain disadvantages associated with the recycling of aluminium such as the presence of impurities, which to a large extent impair the mechanical properties of the recycled material. This problem can be overcome by a careful selection of the constituents and also the fabrication technique, as they can lead to the formation and piling up of intermediate phases that are detrimental [74-76].

There are many interdependent variables to consider in designing an effective MMC material. Since the upper bound on MMC properties is established by the properties of the matrix and reinforcement material, careful selection of these components is necessary.

2.2 MATERIAL SELECTION

2.2.1 Matrix Material

Because it is much more than dispersing glue in MMC, the matrix alloy should be chosen only after giving careful consideration to its chemical compatibility with the reinforcement, to its ability to wet the reinforcement, and to its own characteristics properties and processing behaviour [73, 76].

One very crucial issue to consider in selection of the matrix alloy composition involves the natural dichotomy between wettability of the reinforcement and excessive reactivity with it [77]. Good load transfer from the matrix to the reinforcement depends on the existence of a strongly adherent interface [78, 79]. In turn, a strong interface requires adequate wetting of the reinforcement by the matrix. However, the attainments of wetting and aggressive reactivity are both favored by strong chemical bonding between the matrix and reinforcement. Adjusting the chemical composition to accomplish this delicate compromise is difficult as many subtleties are involved. To illustrate the complexity, several examples concerning alloying additions to aluminium matrix metal relative to Silicon carbide whiskers, Boron reinforced and Graphite reinforced aluminium composites and the effect of insidious impurities from various origins have been documented by numerous investigators [77-91].

As a rule of alloying element addition, the added element should not form intermetallic compounds with the matrix elements and should not form highly stable compounds with the reinforcements. The best properties can be obtained in a composite system when the reinforcement whiskers or particulates and matrix are as physically and chemically compatible as possible. Special matrix alloy compositions, in conjunction with unique whisker coatings, have been devised to optimize the performance of certain metallic composites [92-96].

2.2.2 Why Al Matrix Selection?

MMC materials have a combination of different, superior properties to an unreinforced matrix which are; increased strength, higher elastic modulus, higher service temperature, improved wear resistance, high electrical and thermal conductivity, low coefficient of thermal expansion and high vacuum environmental resistance. These properties can be attained with the proper choice of matrix and reinforcement

Composite materials consist of matrix and reinforcement. Its main function is to transfer and distribute the load to the reinforcement or fibres. This transfer of load depends on the bonding which depends on the type of matrix and reinforcement and the fabrication technique.

The matrix can be selected on the basis of oxidation and corrosion resistance or other properties [34]. Generally Al, Ti, Mg, Ni, Cu, Pb, Fe, Ag, Zn, Sn and Si are used as the matrix material, but Al, Ti, Mg are used widely.

Now a day's researchers all over the world are focusing mainly on aluminium [27] because of its unique combination of good corrosion resistance, low density and excellent mechanical properties. The unique thermal properties of aluminium composites such as metallic conductivity with coefficient of expansion that can be tailored down to zero, add to their prospects in aerospace and avionics. Titanium [30] has been used in aero engines mainly for compressor blades and discs due to its higher elevated temperature resistance properly. Magnesium is the potential material to fabricate composite for making reciprocating components in motors and for pistons, gudgeon pins and spring caps [31]. It is also used in aerospace due to its low coefficient of thermal expansion and high stiffness properties combined with low density. The choice of Silicon Carbide as the reinforcement in aluminium composite is primarily meant to use the composite in missile guidance system replacing certain beryllium components because structural performance is better without special handling in fabrication demanded by latter's toxicity [32,33]. Recently aluminium-lithium alloy has been attracting the attention of researches due to its good wettability characteristics [95].

In addition, literature also reveals that most of the published work has considered aluminium-based composites with their attractions of low density, wide alloy range, heat treatment capability and processing flexibility. Many of these features are also exhibited by magnesium-based systems and with its lower elastic modulus. Magnesium often achieves a larger property improvement with reinforcement than does aluminium also many of the composite fabrication processes are common to both Al and Mg based systems [35, 97].

Magnesium and magnesium alloys are among the lightest candidate materials for practical use as the matrix phase in metal matrix composites. When compared to other currently available structural materials. Magnesium is very attractive because of its unique combination of low density and excellent machinability. However, it has been reported by several authors [98-100] that though their low density (35% lower than that of Al) makes them competitive in terms of strength/density values. Magnesium alloys do not compare favorably with aluminium alloys in terms of absolute strength.

The reason for aluminium being a success over magnesium is said to be mainly due to the design flexibility, good wettability and strong bonding at the interface.

2.2.3 Reinforcement

Reinforcement increases the strength, stiffness and the temperature resistance capacity and lowers the density of MMC. In order to achieve these properties the selection depends on the type of reinforcement, its method of production and chemical compatibility with the matrix and the following aspects must be considered while selecting the reinforcement material.

- Size – diameter and aspect ratio:
- Shape – Chopped fiber, whisker, spherical or irregular particulate, flake, etc:
- Surface morphology – smooth or corrugated and rough:
- Poly – or single crystal:
- Structural defects – voids, occluded material, second phases:
- Surface chemistry – e.g. SiO_2 or C on SiC or other residual films:

- Impurities – Si, Na and Ca in sapphire reinforcement;
- Inherent properties – strength, modulus and density.

Even when a specific type has been selected, reinforcement inconsistency will persist because many of the aspect cited above in addition to contamination from processing equipment and feedstock may vary greatly [101-103]. Since most ceramics are available as particles, there is a wide range of potential reinforcements for particle-reinforced composites [104-108].

The use of graphite reinforcement in a metal matrix has a potential to create a material with a high thermal conductivity, excellent mechanical properties and attractive damping behaviour at elevated temperatures [109]. However, lack of wettability between aluminium and the reinforcement, and oxidation of the graphite [93,110] lead to manufacturing difficulties and cavitations of the material at high temperatures.

Alumina [111] and other oxide particles like TiO_2 [112] etc. have been used as the reinforcing particles in Al-matrix. Alumina has received attention as reinforcing phase as it is found to increase the hardness, tensile strength and wear resistance [111,113] of aluminium metal matrix composites. Rohatgi and co-workers [114-117] have studied mica, alumina, silicon carbide, clay, zircon, and graphite as reinforcements in the production of composites. Numerous oxides, nitrides, borides and carbides were studied by Zedalis et. al. [118] as reinforcements for reinforcing high temperature discontinuously reinforced aluminiumn (HTDRA). It has been inferred from their studies that HTDRA containing TiC TiB_2, B_4C, Al_2O_3, SiC and Si_3N_4 exhibit the highest values of specific stiffness.

It is proven that the ceramic particles are effective reinforcement materials in aluminium alloy to enhance the mechanical and other properties [119-121]. The reinforcement in MMCs are usually of ceramic materials, these reinforcements can be divided into two major groups, continuous and discontinuous. The MMCs produced by them are called continuously (fibre) reinforced composites and discontinuously reinforced composites. However, they can be subdivided broadly into five major categories: continuous fibres, short fibres (chopped fibres, not necessarily the same length), whiskers, particulate and wire (only for metal). With the exception of wires, reinforcements are generally ceramics, typically these ceramics being oxides, carbides and nitrides. These are used because of their combinations of high strength and stiffness at both room and elevated temperatures. Common reinforcement elements are SiC, $A1_20_3$, TiB_2, boron and graphite.

2.2.3.1 Continuous fibre reinforcement

According to ASTM [122] the term fibre may be used for any material in an elongated form that has a minimum length to a maximum average transverse dimension of 10:1, a maximum cross sectional area of $5.1X10^{-4}$ cm^2 and a maximum transverse dimension of 0.0254 cm. Continuous fibers in composites are usually called filaments, the main continuous fibres includes boron, graphite, alumina and silicon carbide.

The fibre is unique for unidirectional load when it is oriented in the same direction as that of loading, but it has low strength in the direction perpendicular to the fibre orientation. As regards cost, continuous fibres are about 200 times higher than discontinuous fibres. Therefore for specific purposes only, that continuous fibre is used. The other advantage of discontinuous fibres is that they can be shaped by any standard metallurgical processes such as forging, rolling, extrusion etc.

2.2.3.2 Short fibres

Short fibres are long compared to the critical length ($l_c = d\ S_f / S_m$ where d is the fibre diameter, S_f is the reinforcement strength and S_m is the matrix strength) and hence show high strength in composites, considering aligned fibres. Nevertheless, misoriented short fibres have been used with some success as AMC (Aluminium Matrix Composite) reinforcement [123-129]. Short fibres are still used mainly for refractory insulation purposes due to their low strength compared with others, but they are cheaper than fibre and whisker.

2.2.3.3 Whiskers

Whiskers are characterized by their fibrous, single crystal structures, which have no crystalline defect. Numerous materials, including metals, oxides, carbides, halides and organic compounds have been prepared under controlled conditions in the form of whiskers. Generally, a whisker has a single dislocation, which runs along the central axis. The relative freedom from discontinuous means that the yield strength of a whisker is close to the theoretical strength of the material [28].

Silicon carbide, silicon nitride, carbon and potassium titanate whiskers are available already. Among these, silicon carbide whiskers seem to offer the best opportunities for MMC reinforcement. Presently, silicon carbide whisker reinforcement is produced from rice husk, which is a low cost material. The physical characteristics of whiskers are responsible for different chemical reactivity with the matrix alloy [130] and also health hazard posed in their handling. Therefore the inherent interest shown by the researches in whiskers reinforcement has declined.

2.2.3.4 Particulates

Particulates are the most common and cheapest reinforcement materials. These produce the isotropic property of MMCs, which shows a promising application in structural fields. Initially, attempts were made to produce reinforced Aluminium alloys with graphite powder [131-138], but only low volume fractions of reinforcement had been incorporated (<10%). Presently higher volume fractions of reinforcements have been achieved for various kinds of ceramic particles (oxide, carbide, nitride). The SiC-particulate-reinforced aluminium matrix composites have a good potential for use as wear resistant materials. Actually, particulates lead to a favorable effect on properties such as hardness, wear resistance and compressive strength.

The choice of reinforcement is not as arbitrary as this list of composites might suggest, but is dictated by several factors [36].

- **The application**: If the composite is to be used in a structural application, the modulus, strength, and density of the composite will be important, which requires a high modulus, low density reinforcement. Particle shape may be important, since angular particles can act as local stress raisers, reducing ductility. If the composite is to be used in thermal management applications, the coefficient of thermal expansion and thermal conductivity are important. If the composite is to be used in wear resistant applications, hardness is important.
- **The method of composite manufacture**: There are two generic methods for composite manufacture, powder metallurgy (P/M) and methods involving molten metal. For composites processed in the molten state, there are different considerations such as, compatibility. Alumina is stable in most Mg free Al alloys, but unstable in Mg alloys, reacting to form Al_2MgO_4. Reaction of the reinforcement can severely degrade the properties of the composites, so the reinforcement has to be chosen after considering the matrix alloy, and the processing time and temperature.

- **Cost:** A major concern for using particulates is to reduce the cost of the composites. Therefore, the reinforcement of reproducible grade has to be readily available in quantities, size and shape required at low cost.

2.3 FABRICATION METHODS OF MMCs

In recent years the potential of metal-matrix composite (MMC) materials for significant improvement in performance over conventional alloys has been recognized widely. However, their manufacturing costs are still relatively high. There are several fabrication techniques available to manufacture the MMC materials: there is no unique route in this respect. Due to the choice of material and reinforcement and of the types of reinforcement, the fabrication techniques can vary considerably. The processing methods used to manufacture particulate reinforced MMCs can be grouped as follows.

- **Solid-phase fabrication methods**: diffusion bonding, hot rolling, extrusion, drawing, explosive welding, PM route, pneumatic impaction, etc. [139-140].

- **Liquid-phase fabrication methods**: liquid-metal infiltration, squeeze casting, compocasting, pressure casting, spray codeposition, stir casting etc.[139-140].

- **Two phase (solid/liquid) processes:** Which include Rheocasting [141] and Spray atomization [142].

Normally the liquid-phase fabrication method is more efficient [143] than the solid-phase fabrication method because solid-phase processing requires a longer time.

The matrix metal is used in various forms in different fabrication methods. Generally powder is used in pneumatic impaction and the powder metallurgy technique, and a liquid matrix is used in liquid-metal infiltration, plasma spray, spray casting, squeeze casting, pressure casting, gravity casting, stir casting, investment casting, etc. A molecular form of the matrix is used in electroforming; vapour deposition and metal foils are used in diffusion bonding, rolling, extrusion, etc.

There are certain main manufacturing processes which are used presently in laboratories as well as in industries are diffusion bonding, the powder metallurgy route, liquid-metal infiltration, squeeze casting, spray co-deposition, stir casting and compo casting. Brief Description of these processes is given below.

2.3.1 Solid phase fabrication methods

There are several ways to fabricate MMC using solid-phase materials but among them diffusion bonding and the powder metallurgy route are used widely.

2.3.1.1 Diffusion bonding

This method is normally used to manufacture fibre reinforced MMC with sheets or foils of matrix material. Figure 2.1 [139] shows the different steps in fabricating MMC by diffusion bonding.

Here primarily the metal or metal alloys in the form of sheets and the reinforcement material in the form of fibre are chemically surface treated for the effectiveness of interdiffusion. Then fibres are placed on the metal foil in pre-determined orientation and bonding takes place by press forming directly, as shown by the dotted line. However sometimes the fibres are coated by plasma spraying or ion plating for enhancing the bonding strength before diffusion bonding, the solid line shows this. After bonding, secondary machining work is carried out. The applied pressure and temperature as well as their durations for diffusion bonding to develop, vary with the composite systems. However, this is the most expensive method of fabricating MMC materials.

2.3.1.2 Powder metallurgy (PM) technique

The PM technique shown in Fig. 2.2 is the most commonly used method for the preparation of discontinuous reinforced MMCs [140]. This technique is used to manufacture MMCs using either particulates or whiskers as the reinforcement materials. In general process the powders of matrix materials and reinforcement are first blended and fed into a mould of the desired shape. Pressure is then applied to further compact the powder (cold pressing). In order to facilitate the bonding between the powder particles, the compact is then heated to a temperature that is below the melting point but sufficiently high to develop significant solid-state diffusion (sintering). The consolidated product is then used as a MMC material after some secondary operation.

This method is popular because it is reliable compared with other alternative methods, but it has also some demerits. The blending step is a time consuming, expensive and potentially dangerous operation. In addition, it is difficult to achieve an even distribution of particulate throughout the product and the use of powders requires a high level of cleanliness, otherwise inclusions will be incorporated into the product with a deleterious effect on fracture toughness, fatigue life, etc.

2.3.2 Liquid phase fabrication techniques

Most of the MMCs are produced by this technique. In this technique, the ceramic particles are incorporated into liquid metal using various processes. The liquid composite slurry is subsequently cast into various shapes by conventional casting techniques or cast into ingots for secondary processing. The process has major advantage that the production costs of MMCs are very low. The major difficulty in such processes is the non-wettability of the particles by liquid aluminium and the consequent rejection of the particles from the melt, non-uniform distribution of particles due to their preferential segregation and extensive interfacial reaction.

2.3.2.1 Liquid metal infiltration

This process can also be called fibre-tow infiltration. Fibers tows can be infiltrated by passing through a bath of molten metal. Usually the fibres must be coated in line to promote wetting. Once the infiltrated wires are produced, they must be assembled into a preform and given a secondary consolidation process to produce a component. Secondary consolidation is generally accomplished through diffusion bonding or hot moulding in the two-phase liquid and solid region.

The fabrication process of MMC by vacuum metal infiltration used by Chapman et al. [144] is shown in Fig. 2.3. These authors used Aluminium oxide fibre FP (polycrystalline fibre) of Du Pont Company. In this technique, as the first step, FP yarn is made into a handleable FP tape with a fugitive organic binder in a manner similar to producing a resin matrix composite prepeg. Fibre FP tapes are then laid-up in the desired orientation, fibre volume loading, and shape, and are then inserted into a casting mold of steel or other suitable material. The fugitive organic binder is burned away, and the mold is infiltrated with molten metal and allowed to solidify. Metals such as Aluminium, magnesium, silver and copper have been used as the matrix materials in this liquid infiltration process because of their relatively lower melting points. This method is desirable in producing relatively small-size composite specimens having unidirectional properties.

2.3.2.2 Squeeze casting

Squeeze casting is a one-step metal forming process in which a metered quantity of liquid metal in a reusable die is subjected to a rapid solidification under high pressures (50 to 100 MPa) to produce close-tolerance, high-integrity finished shapes. The fabrication process of MMC by squeeze casting is shown in Fig. 2.4. The preform of the ceramic fibre is pre-heated to several hundred degrees centigrade below the melting temperature of the matrix and then set into a metal die. The Al or Mg alloy is heated to just above its melting temperature and is then squeezed into the fibre preform by a hydraulic press to form a mixture of fibre and molten metal.

This process can be used for large scale manufacturing but it requires careful control of the process variables, including the fiber and liquid metal preheat temperature, the metal alloying elements, external cooling, the melt quality, the tooling temperature, the time lag between die closure and pressurization, the pressure levels and duration and the plunger speed. Imperfect control of these process variables results in various defects, including freeze chocking, preform deformation, fiber degradation, oxide inclusions and other common casting defects. However, in practical use, squeeze casting is the most effective method of constructing a machine parts with a complex shape in a short time.

2.3.2.3 Spray co-deposition method

Spray-deposition method is an economical method of producing a particulate composite. A schematic of the Alcan spray deposition process is shown in Fig. 2.5. The alloy to be sprayed is melted in a crucible by induction heating. The crucible is pressurized and the metal is ejected through a nozzle into an atomizer where, at the same time, particles (reinforcement) are injected into the atomized metal and deposited on a pre-heated substrate placed in the line of flight. A solid deposit is built up on the collector. The deposited strip, when cold, is moved from the substrate for subsequent rolling. The shape of the final product depends on the atomizing condition and the shape and the motion of the collector.

2.3.2.4 Stir casting

Stir-casting techniques shown in Fig. 2.6 are currently the simplest and most commercial method of production of MMCs. This approach involves mechanical mixing of the reinforcement particulate into a molten metal bath and transferred the mixture directly to a shaped mould prior to complete solidification. In this process, the crucial thing is to create good wetting between the particulate reinforcement and the molten metal.

. Microstructural inhomogeneties can cause notably particle agglomeration and sedimentation in the melt and subsequently during solidification. Inhomogeneity in reinforcement distribution in these cast composites could also be a problem as a result of interaction between suspended ceramic particles and moving solid-liquid interface during solidification. This process has major advantage that the production costs of MMCs are very low.

2.3.2.5 Compocasting

Other than PM, thermal spraying, diffusion bonding and high-pressure squeeze casting, this is the most economical method of fabricating a composite with discontinuous fibres (chopped fibre, whisker and particulate). This process is the improved process of slush- or stir-casting.

A schematic of the compo casting equipment used to fabricate the composites is shown in Fig. 2.7. The apparatus consists of an induction power supply (50 kW, 3000 Hz), a water-cooled vacuum chamber with its associated mechanical and diffusion pumps and a crucible and mixing assembly for agitation of the composites.

First, a metal alloy is placed in the system with the blade assembly in place. Then the chamber is evacuated and the alloy is superheated above its melting temperature and stirring is initiated by the DC motor to homogenize the temperature. The induction power is lowered gradually until the alloy is 40 to 50% solid, at which point the non-metallic particles are added to the slurry, However, the temperature is raised during adding in such a way that the total amount of solid, which consists of fibres and solid globules of the slurry, does not exceed 50%. Stirring is continued until interface interactions between the particulates and the matrix promote wetting.

The melt is then superheated to above its liquid temperature and bottom poured into the graphite mould by raising the blade assembly. The melt containing the non-metallic particles is then transferred into the lower die-half of the press and the top die is brought down to shape and solidify the Composite by applying the pressure. This is using to make the composite of the highest values of volume fractions of reinforcement.

Literature in general, suggests that MMCs will be less forgiving in terms of processing practice than unreinforced alloys, but if the appropriate practice is employed, useful combinations of mechanical and physical properties can be obtained.

2.4 MECHANICAL PROPERTIES

The attractive physical and mechanical properties that can be obtained with metal matrix composites, such as high specific modulus, strength and thermal stability, have been documented extensively [145-147]. The various factors controlling the properties of particulate MMCs [41] and the influence of the manufacturing route on the MMC properties has also been reviewed by several investigators [148-150]. Improvement in modulus, strength, fatigue, creep and wear resistance has already been demonstrated for a variety of reinforcements [38, 151]. Of these properties; the tensile strength is the most convenient and widely quoted measurement and is of central importance in many applications.

It is apparent from the literature that parameters controlling the mechanical properties of particulate reinforced composites are still not understood in any detail. However, some of the important factors are becoming apparent.

- The strength of particle-reinforced composites is observed to be most strongly dependent on the volume fraction and particle size of the reinforcement.

- Dislocation strengthening will play a more significant role in the MMC than in the unreinforced alloy due to the increased dislocation density.

- Of greatest concern appears to be the introduction of defects and inhomogeneities in the various processing stages, which has been found to result in considerable scatter in the mechanical properties [152].

2.5 EFFECT OF REINFORCEMENT VOLUME FRACTION

It was predicted by Friend [153] that there exists a critical reinforcement volume fraction above which the composite strength can be improved relative to that of the unreinforced material and below which the composite strength decreases, owing to the ineffective load transfer from matrix to reinforcement in MMCs. For low volume fraction of reinforcement, the composite strength was observed to be governed by the residual matrix strength, which decreases with increasing reinforcing volume fraction.

2.5.1 Effect of particle size

The deformation and fracture behaviour of the composite revealed the importance of particle size [153]. A reduction in particle size is observed [154] to increase the proportional limit, yield stress and the ultimate tensile stress. It is well established that large particles are detrimental to fracture toughness due to their tendency towards fracture. It would be highly desirable to have a composite system where the reinforcing particles are relatively fine (4µm or less) so as to get the stiffness benefits of a composite without significantly lowering fracture toughness.

2.5.2 Effect of reinforcement distribution

Apart from the reinforcement level, the reinforcement distribution also influences the ductility and fracture toughness of the MMC and hence indirectly the strength [155]. A uniform reinforcement distribution is essential for effective utilization of the load carrying capacity of the reinforcement. Non-uniform distributions of reinforcement in the early stages of processing was observed to persist to the final product in the forms of streaks or clusters of uninfiltrated reinforcement with their attendant porosity, all of which lowered ductility, strength and toughness of the material [77].

2.6 FRACTURE

The fracture behaviour of MMCs has been identified not only for extending their applications but also for improving mechanical properties, especially strength and ductility.

A better understanding of the underlying mechanisms affecting composite properties are essential if the properties of the composite material are to be improved. The fundamentals of fracture initiation and propagation mechanism in particle-reinforced composites have been discussed in detail by Bhanuprasad et al. [156]. Tensile fracture of conventional alloys is considered in terms of the micro void coalescence model (MVC). Void nucleation in unreinforced alloys occurs at constituent particles, either through particle failure, through interface decohesion. Decohesion is most common, but particle cracking occurs with elongated particles. In composites, there are three possible mechanisms for void nucleation particle cracking, interface decohesion, and matrix void nucleation is the same mechanism as occurs in the unreinforced alloys

2.7 MICROSTRUCTURE

The most important aspects of the microstructure is the distribution of the reinforcing particles, and this depends on the processing and fabrication routes involved. The oxides of reinforcing particles used in the composites have a varying density. Density of the particles is one of the important factors determining the distribution of the particles in molten metal. Particles having higher density than molten metal can settle at the bottom of the bath slowly and particles of lower density can segregate at the top. During subsequent pouring of the composite melt, the particle content may vary from one casting to another or even it can vary in the same casting from one region to another. Therefore uniform distribution of the particles in the melt is a necessary condition for uniform distribution of particles in the castings. The properties of composites are finally dependent on the distribution of the particles. Hence the study of the distribution of the particles in the composite is of great significance. Several investigators [156-160] have examined the fracture samples of different metal matrix composites; it was observed that the fracture occurred mainly through the matrix in a ductile manner.

2.8 RESULTS AND DISCUSSION

A detailed study was undertaken to pool-up the existing literature on Aluminium based MMCs and efforts were put to understand the basic needs of the growing Composite industry. This includes various aspects such as Characterization, fabrication, testing, analysis and correlation between microstructure and the properties obtained.

The conclusions drawn from this study are

- Pure aluminium matrix is preferred to various alloy matrices due to the high temperature stability of the aluminium as compared with aluminium alloys. Lower working temperature's in case of alloy matrices is attributed to lower stability of the alloy matrix and coarsening of the grains. In addition, the load transfer in case of pure aluminium matrix is more effective due to the clean interface.

- There exists a wide range of database in the literature for different types of reinforcements in Aluminium Metal Matrix Composites.

- In particle reinforced composites, the fracture mode was observed to depend on reinforcement purity, reinforcement particle size, nature of interface, volume fraction of reinforcement, fabrication route adopted, extent of hot working, presence of any intermetallic precipitates and extent of coherency of second phase with the matrix.

- There are varieties of techniques available for production of metal matrix composite. Each having its own merits and demerits.. In particular, some are far more expensive than others. The manufacturer generally prefers the lowest cost route. Therefore, stir-casting technique represents a substantial proportion of the MMCs in commercial sectors today.

Thus the priority of this work will be to prepare MMC using red mud (an industrial waste from Bayer's process) as reinforcement material and to study its wear characteristics. The effect of different dependant factors primarily sliding velocity, normal load, effect of heat treatment temperature and cooling media are also to be studied.

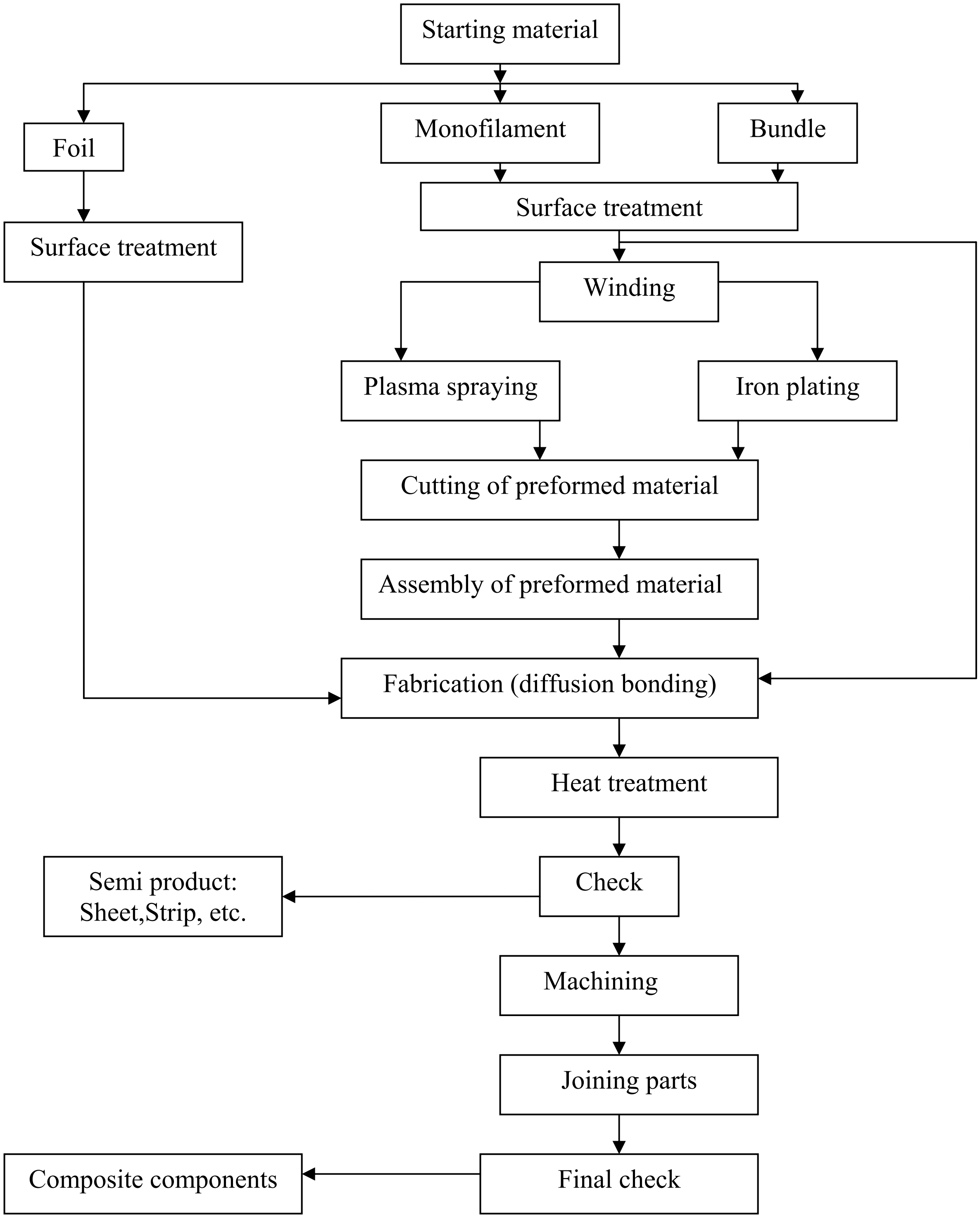

Fig.2.1 Flow chart for composite fabrication by diffusion bonding

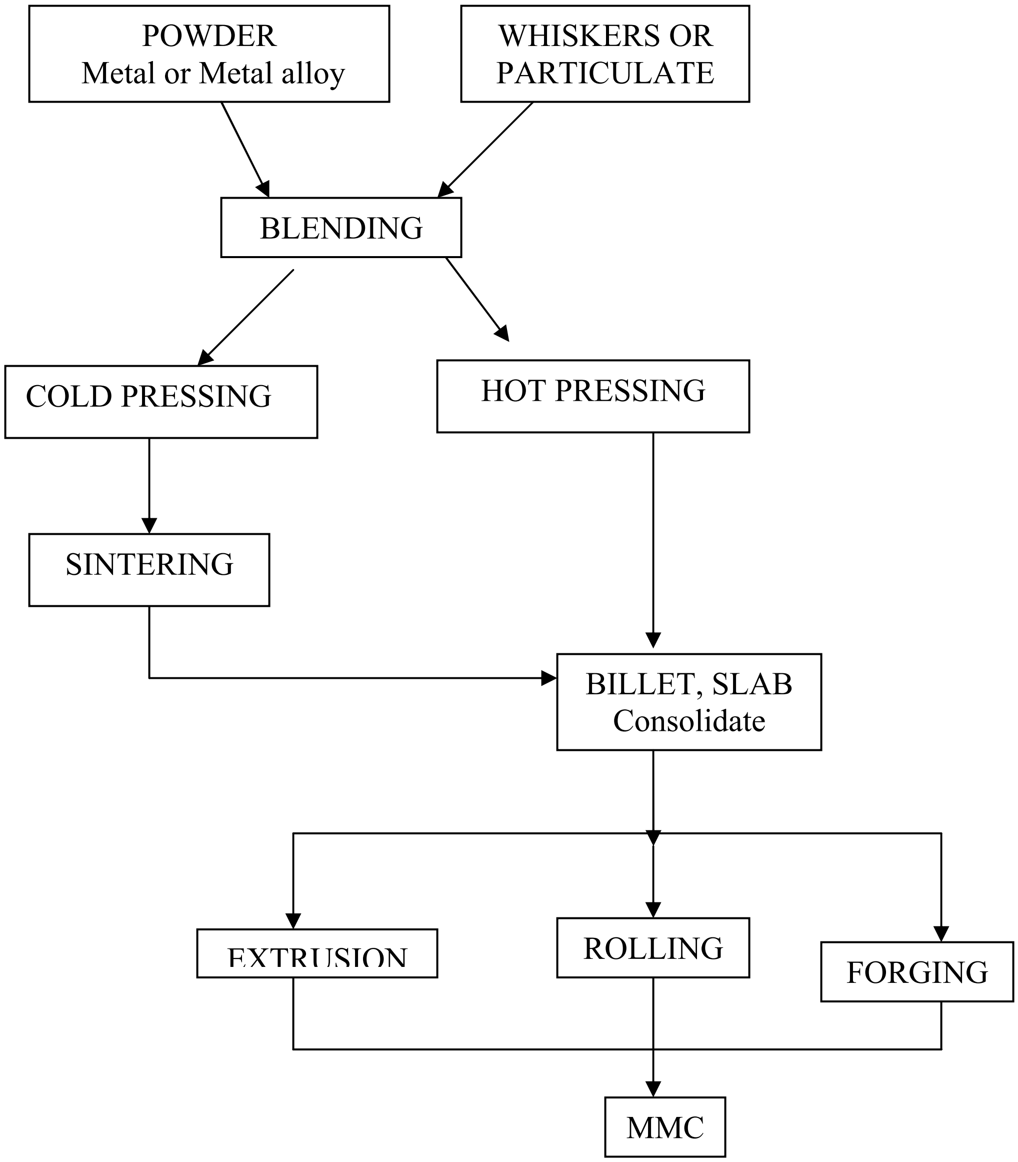

Fig.2.2 General flow chart for fabrication of composite by powder metallurgy technique

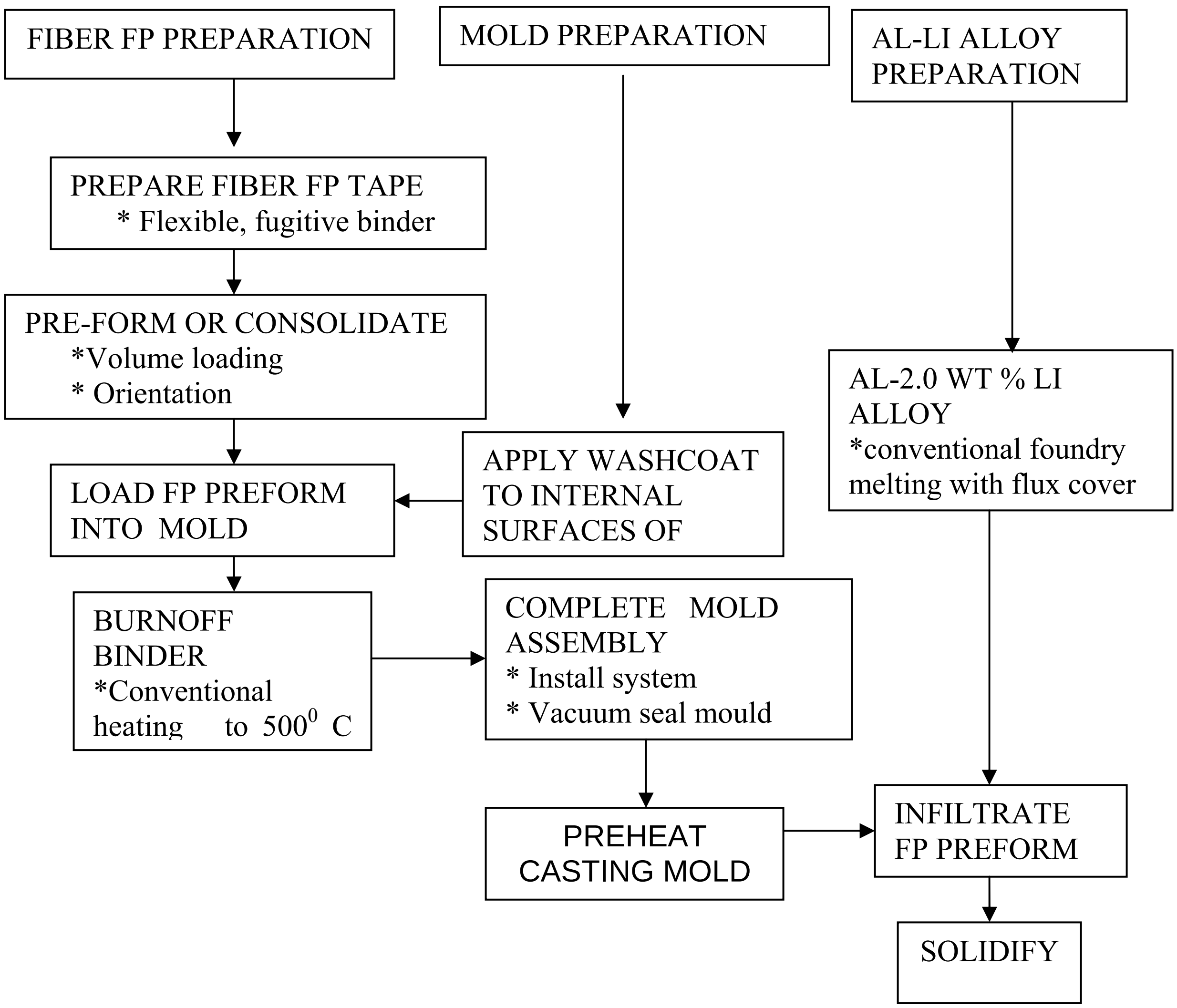

Fig. 2.3 Flow chart for FP/Al plate casting

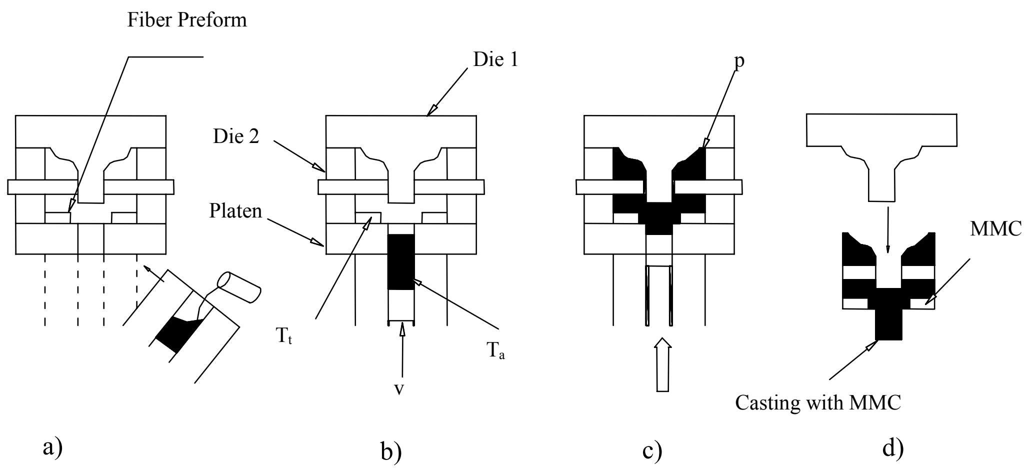

Fig.2.4 Sequences of the Squeeze casting process with a vertical machine (a) pouring (b) casting (c) squeezing and (d) ejecting

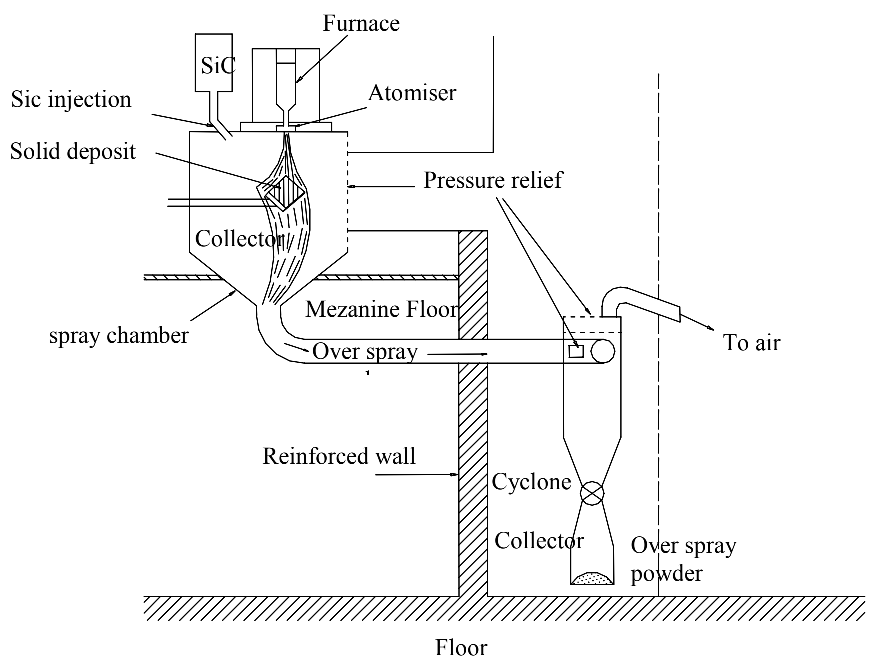

Fig. 2.5 Schematic of spray deposition equipment

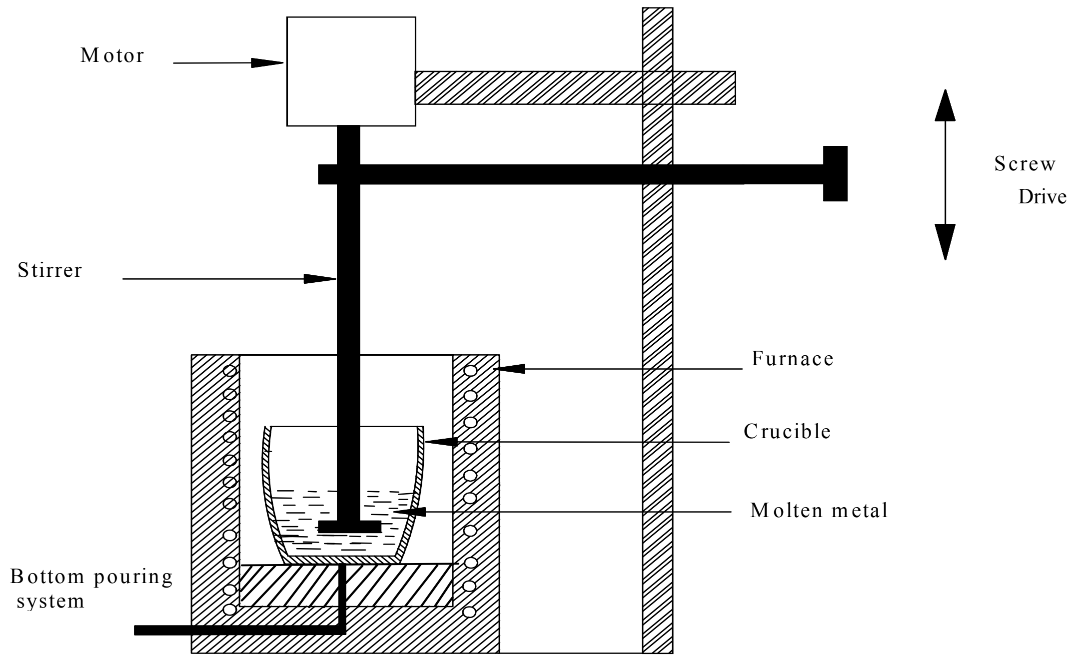

Fig.2.6 MMC by casting route through Stir Casting method

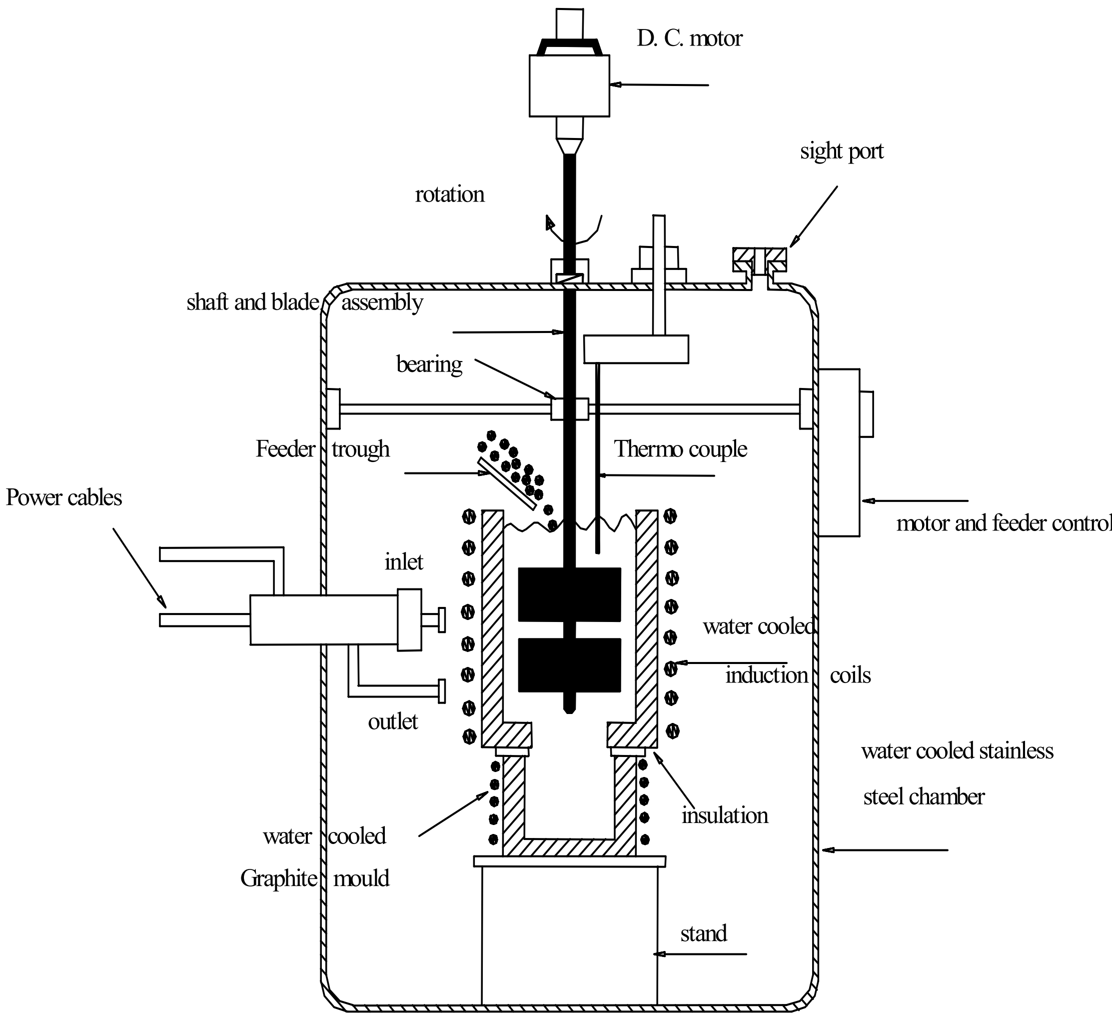

Fig. 2.7 Compocasting: mixing fibres (or Particulates) with metal

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CHAPTER - 3

EXPERIMENTAL STUDY OF WEAR CHARACTERISTICS OF ALUMINIUM RED MUD COMPOSITE

3.1 INTRODUCTION

Wear of metals is probably the most important yet at least understood aspects of tribology. It is certainly the youngest of the tri of topics, friction, lubrication and wear, to attract scientific attention, although its practical significance has been recognizes throughout the ages. The findings of Guillaume Amontons in 1699 [161] establishing scientific studies of friction are almost of 300 years age, while Petrov [162], Tower [163] and Reynolds [164] brought enlightenment to the subject of lubrication a century ago in the hectic 1880s. Substantial Studies of wear can be associated only with the five decades that have elapsed since R.Holm [165] explored the fundamental aspects of surface interactions encountered in electrical contacts.

One third of our global energy consumption is consumed wastefully in friction. In addition to this primary saving of energy, very significant additional economics can be made by the reduction of the cost involved in the manufacture and replacement of prematurely worn out components. The dissipation of energy by wear impairs strongly the national economy and the life style of most of people. So, the effective decrease and control of wear of metals are always desired [166].

Wear causes an enormous annual expenditure by industry and consumers. Most of this is replacing or repairing equipment that has worn to the extent that it no longer performs a useful function. For many machine components this occurs after a very small percentage of the total volume has been worn away. For some industries, such as agriculture, as many as 40% of the components replaced on equipment have failed by abrasive wear. Other major sources of expenditure are losses production consequential upon lower efficiency and plant shutdown, the need to invest more frequently in capital equipment and increased energy consumption as equipment wears. Estimates of direct cost of abrasive wear to industrial nations vary from 1 to 4 % of gross national product and Rigney [167] has estimated that about 10% of all energy generated by man is dissipated in various friction processes.

Wear is not an intrinsic material property but characteristics of the engineering system which depend on load, speed, temperature, hardness, presence of foreign material and the environmental condition [168]. Widely varied wearing conditions causes wear of materials. It may be due to surface damage or removal of material from one or both of two solid surfaces in a sliding, rolling or impact motion relative to one another. In most cases wear occurs through surface interactions at asperities. During relative motion, material on contacting surface may be removed from a surface, may result in the transfer to the mating surface, or may break loose as a wear particle. The wear resistance of materials is related to its microstructure may take place during the wear process and hence, it seems that in wear research emphasis is placed on microstructure [169]. Wear of metals depends on many variables, so wear research programs must be planned systematically. Therefore researchers have normalized some of the data to make them more useful. The wear map proposed by Lim and Ashby [168] is very much useful in this regard to understand the wear mechanism in sliding wear, with or without lubrication.

3.2 RECENT TRENDS IN METAL WEAR RESEARCH

Much of the wear researches carried out in the 1940’s and 1950’s were conducted by mechanical engineers and metallurgists to generate data for the construction of motor drive, trains, brakes, bearings, bushings and other types of moving mechanical assemblies [170].

It became apparent during the survey that wear of metals was a prominent topic in a large number of the responses regarding some future priorities for research in tribology. Some 22 experienced technologists in this field, who attended the 1983 ‘Wear of Materials Conference’ in Reston, prepared a ranking list [171]. Their proposals with top priority were further investigations of the mechanism of wear and this no doubt reflects the judgments that particular effects of wear should be studied against a background of the basic physical and chemical processes involved in surface interactions. The list proposed is shown in table 3.1.

Peterson [166] reviewed the development and use of tribo-materials and concluded that metals and their alloys are the most common engineering materials used in wear applications. Grey cast iron for example has been used as early as 1388. Much of the wear research conducted over the past 50 years is in ceramics, polymers, composite materials and coatings [172].

Table – 3.1

Priority in wears research [171]

Ranking	Topics
1.	Mechanism of Wear
2.	Surface Coatings and treatments
3.	Abrasive Wear
4.	Materials
5.	Ceramic Wear
6.	Metallic Wear
7.	Polymer Wear
8.	Wear with Lubrication
9.	Piston ring-cylinder liner Wear
10.	Corrosive Wear
11.	Wear in other Internal Combustion Machine Components

Wear of metals encountered in industrial situations can be grouped into categories shown in table 3.2. Though there are situations where one type changes to another or where two or more mechanism plays together.

Table - 3.2

Type of wear in industry [170]

Type of wear in Industry	Approximate percentage involved
Abrasive	50
Adhesive	15
Erosion	8
Fretting	8
Chemical	5

3.3 THEORY OF WEAR

Wear occurs as a natural consequence when two surfaces with a relative motion interact with each other. Wear may be defined as the progressive loss of material from contacting surfaces in relative motion. Scientists have developed various wear theories in which the Physico-Mechanical characteristics of the materials and the physical conditions (e.g. the resistance of the rubbing body and the stress state at the contact area) are taken in to consideration. In 1940 Holm [165] starting from the atomic mechanism of wear, calculated the volume of substance worn over unit sliding path.

Barwell and Strang [173] in 1952: Archard [174] in 1953 and Archard and Hirst [175] in 1956 developed the adhesion theory of wear and proposed a theoretical equation identical in structure with Holm's equation. In 1957, Kragelski developed the fatigue theory of wear. Because of the Asperities in real bodies their interactions on sliding is discrete and contact occurs at individual locations, when taken together, form the real contact area. Under normal force the asperities penetrate into each other or are flattened out and in the region of real contact points corresponding stress and strain rise. In sliding, a fixed volume of material is subjected to the many times repeated action, which weakens the material and leads finally to rupture.

Though all the theories are based on different mechanisms of wear, the basic consideration is the frictional work. Hence friction is the prime consideration.

In the last two decades numerous studies of wear properties of Aluminium based Metal Matrix Composites with different type of reinforcements has been studied. Kirit J. Bhansali and Robert Mehrabian [38] have studied the abrasive wear resistance of aluminum matrix composites containing Al_2O_3 and SiC using a dry sand/rubber wheel abrasion tester. Their results show that composites containing Al_2O_3 were found to be superior to those containing SiC. G.Wang, & I.M. Huttching [39] reported the investigations of the response of alumina fiber- aluminum metal matrix composites systems to wear by two-body abrasion. Their results show that wear resistance of the composites was found to range from almost two to six times that of the unreinforced matrix alloy. A.T. Alpas and J.Zhang [42] studied the dry sliding wear of aluminum matrix composites and determined how the micro structural parameters such as volume fraction of particulate and particulate size affect the wear resistance of these materials. V.Constantin et. al. [176] investigated the sliding wear behaviour of Aluminum Silicon Carbide metal matrix composites reinforced with different volume fraction of particulate against a stainless steel slider. Their results show that addition of reinforced particles increases the resistance of the composites to sliding wear under dry conditions, even for small volume fraction of particles. Rohatgi.P.K et. al. [43] in their work report test examination of abrasive wear resistance of Aluminum alloy (A356) containing fly-ash particles. Their results show that the wear resistance of specimen containing fly ash was comparable to that of alumina fiber-reinforced alloy and superior to that of base A356 alloy.T.Miyajima,& Y.Iwai [177] studied the effect of reinforcements on sliding wear behaviour of aluminum matrix composites. Their results show that the degree of improvement of wear resistance of metal matrix composites (MMC) is strongly dependent on the kind of reinforcement as well as its volume fraction. Aluminum metal matrix composites are emerging as promising friction materials. One of the important applications that is being considered for MMCs is as rotor (disc/drum) material in automotive brake system. K.M.Shorowordi et. al. [125] studied the effect of velocity on the wear, friction and tribochemistry of aluminum MMC sliding against phenolic brake pad. Their results show that higher sliding velocity leads to lower wear rate and lower friction coefficient for Al-B_4C and Al-SiC metal matrix composites. Hutching I.M [178] studied the "Tribological properties of Metal Matrix Composites" and have the opinion that under certain conditions MMCs show high wear resistance but this is not the case always and is some time depended on the wear mechanism. Axen et. al. [123] studied the friction and wear behaviour of an Al-Si, Mg-Mn aluminum alloy reinforced with 10%, 15%, and 30% volume of alumina fibers. Their results shows that fiber reinforcement increases the wear resistance in milder abrasion situations and the coefficient of friction decreases with increasing fiber content and matrix hardness of composites. Zongy Ma Jing et. al. [124] studied the abrasive wear of discontinuous SiC reinforced aluminum alloy composites. Their result shows that the composites exhibits excellent abrasive resistance compared with the unreinforced matrix alloy. A.Alahelisten et. al. [50] studied the effect of fiber reinforcement of aluminum magnesium and Mg-9 Al-1 Zn on the wear properties. Their results shows that tribological behaviour of MMCs depends much on type of MMC and the type of contact situation i.e. tribosystem. L. Cao et. al. [128] studied the wear behaviour of a SiC whisker reinforced aluminum composite. Their results show that the SiC whisker–Al composite exhibits a fairly good wear resistance especially for higher sliding velocities and / or higher loads. Liang.Y.N et.al. [127] studied the effect of particle size on the wear behaviour of SiC particulate reinforced 2024 Al composites investigated using three tests, sliding wear test, impact abrasion test, and erosion test. Their results show that the wear behaviour of particulate reinforced aluminum composite is significantly affected by particle size. Composites contain large particles exhibited excellent wear under sliding wear conditions with steady applied load. Wang and Rack [41] studied on the comparative assessment of the effect of different types of reinforcement. Their results show that in the case of 20% vol. SiC particles Vs 20% Volume SiC-whisker (perpendicular or parallel), the steady state wear rates of the composites were generally independent of the reinforcement geometry (Particulate or whisker) and orientation (perpendicular Vs Parallel).A.Ravikiran, M. K. Surappa [129], studied the effect of sliding speed on wear behaviour of Al-30 wt % SiCp MMC, concluded that the wear rate of pin material (MMC) decreases with increasing speed, and also the wear rate of the composite decreases with increasing area fraction of SiC particles. Manish Narayan et. al. [179] have done an experimental study on dry sliding wear behaviour of Al alloy 2024 Al_2O_3 particle metal matrix composites and have shown that the Al 2014, 15 vol% Al_2O_3 composite shows better seizure resistance than does the unreinforced alloy in the peak aged condition and also in the as-extruded condition the wear resistance of the unreinforced alloy is better than that of composite.

As reported earlier the fabrication techniques for MMCs vary depending upon choice of matrix material and the type of reinforcement. Tjong. S.C et. al. [53] studied the wear behaviour of aluminum silicon alloy reinforced with low volume fraction of SiC particles prepared by Compo Casting process. The wear behaviour of unreinforced Al-12 % SiC alloy and metal matrix composites was investigated by them using a block–on-ring test at room temperature under dry conditions. Their result shows that the addition of low volume fraction of SiC particles (2 to 8%) is a very effective way of increasing wear resistance of composite. Yoshiro.Iwai et. al. [126] studied the wear properties of SiC whisker reinforced 2024 Al alloy with volume fraction of whiskers ranging from 0 to 16% produced by Powder Metallurgy technique. Their results show that SiC whisker reinforcement can improve the wear resistance of aluminum alloy for both severe and mild wear. D. Huda et. al. [139, 95] reported that a particular fabrication technique depends on the type of the proper matrix and reinforcement materials to form the MMC.

Sannino and Rack [44] however showed that the effect of the shape of reinforcement depends on the sliding velocity. It is difficult to deduce the effects of reinforcement from the literature because in the reported studies experimental conditions such as contact load and sliding velocity spread over very wide ranges and these studies employ different kinds of test apparatus. The effects of sliding velocity on the frictional and wear behavior of aluminum MMC sliding against ferrous counter body have been studied by a number of researchers [180-182]. Their studies reveled that the frictional and wear characteristics of aluminum MMC depend on the sliding speed in a complicated way. Depending upon the sliding velocity range, both increase and decrease in wear rate with sliding velocity were reported.

It is clear from the above discussions that the wear properties are improved remarkable by introducing a hard inter metallic compound into the aluminum matrix [56]. It has also been demonstrated that because the bonding strength between intermetallic and matrix is very strong, pulling out is prevented even at high loads [183]. The Wear of aluminum based metal matrix composites (MMCs) depends on several factors such as volume fraction, morphology, and size of reinforcing phase as well as the strength of the interface. Work published in the literature is mainly concerned with SiC, Al_2O_3 particles. There are also relatively few discussions on the wear behavior of aluminum MMCs reinforced with alumna fibers [54] and also with natural minerals [55]. But till now as per the information of the investigator no work has been done with red mud as reinforcement. Therefore the present investigation is aimed at preparation of a Metal Matrix Composite using red mud as reinforcing material and to study its friction and wear behaviour.

3.4 TYPES OF WEAR

In most basic wear studies where the problems of wear have been a primary concern, the so-called dry friction has been investigated to avoid the influences of fluid lubricants.

Dry friction' is defined as friction under not intentionally lubricated conditions but it is well known that it is friction under lubrication by atmospheric gases, especially by oxygen [184].

A fundamental scheme to classify wear was first outlined by Burwell and Strang [185]. Later Burwell [186] modified the classification to include five distinct types of wear, namely (1) Abrasive (2) Adhesive (3) Erosive (4) Surface fatigue (5) Corrosive.

3.4.1 Abrasive wear

Abrasive wear can be defined as wear that occurs when a hard surface slides against and cuts groove from a softer surface. It can be account for most failures in practice. Hard particles or asperities that cut or groove one of the rubbing surfaces produce abrasive wear. This hard material may be originated from one of the two rubbing surfaces. In sliding mechanisms, abrasion can arise from the existing asperities on one surface (if it is harder than the other), from the generation of wear fragments which are repeatedly deformed and hence get work hardened for oxidized until they became harder than either or both of the sliding surfaces, or from the adventitious entry of hard particles, such as dirt from outside the system.

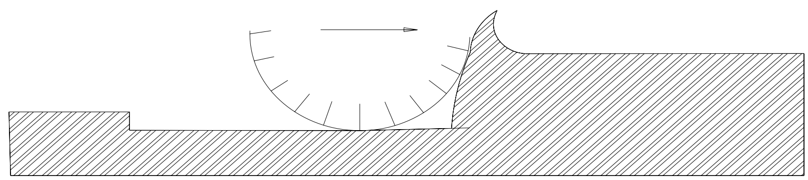


Fig. 3.1 Schematic representations of the abrasion wear mechanism

Two body abrasive wear occurs when one surface (usually harder than the second) cuts material away from the second, although this mechanism very often changes to three body abrasion as the wear debris then acts as an abrasive between the two surfaces. Abrasives can act as in grinding where the abrasive is fixed relative to one surface or as in lapping where the abrasive tumbles producing a series of indentations as opposed to a scratch. According to the recent tribological survey, abrasive wear is responsible for the largest amount of material loss in industrial practice (187).

3.4.2 Adhesive wear

Adhesive wear can be defined as wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or the loss from either surface. For adhesive wear to occur it is necessary for the surfaces to be in intimate contact with each other. Surfaces, which are held apart by lubricating films, oxide films etc. reduce the tendency for adhesion to occur.

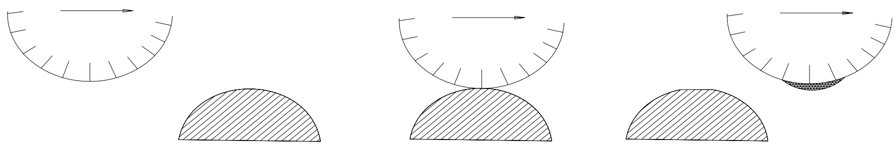


Fig .3.2 Schematic representations of the adhesive wear mechanism

3.4.3 Erosive wear

Erosive wear can be defined as the process of metal removal due to impingement of solid particles on a surface. Erosion is caused by a gas or a liquid, which may or may not carry, entrained solid particles, impinging on a surface. When the angle of impingement is small, the wear produced is closely analogous to abrasion. When the angle of impingement is normal to the surface, material is displaced by plastic flow or is dislodged by brittle failure.

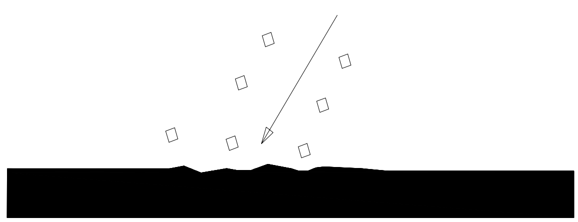


Fig. 3.3 Schematic representations of the erosive wear mechansim

3.4.4 Surface fatigue wear

Wear of a solid surface caused by fracture arising from material fatigue. The term 'fatigue' is broadly applied to the failure phenomenon where a solid is subjected to cyclic loading involving tension and compression above a certain critical stress. Repeated loading causes the generation of micro cracks, usually below the surface, at the site of a pre-existing point of weakness. On subsequent loading and unloading, the micro crack propagates. Once the crack reaches the critical size, it changes its direction to emerge at the surface, and thus flat sheet like particles is detached during wearing. The number of stress cycles required to cause such failure decreases as the corresponding magnitude of stress increases. Vibration is a common cause of fatigue wear.

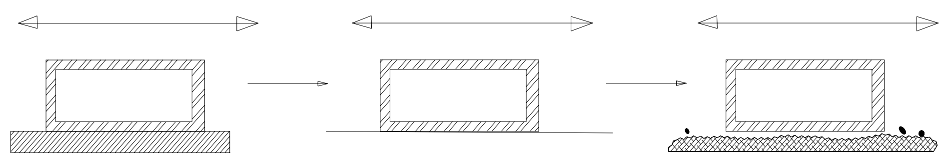


Fig. 3.4 Schematic representations of the surface fatigue wear mechanism

3.4.5 Corrosive wear

Most metals are thermodynamically unstable in air and react with oxygen to form an oxide, which usually develop layer or scales on the surface of metal or alloys when their interfacial bonds are poor. Corrosion wear is the gradual eating away or deterioration of unprotected metal surfaces by the effects of the atmosphere, acids, gases, alkalis, etc. This type of wear creates pits and perforations and may eventually dissolve metal parts.

3.5 SYMPTOMS OF WEAR

A summary of the appearance and symptoms of different wear mechanism is indicated in Table 3.3 and the same is a systematic approach to diagnose the wear mechanisms.

Table - 3.3

Symptoms and appearance of different types of wear [188]

Types of wear	Symptoms	Appearance of the worn-out surface
Abrasive	Presence of clean furrows cut out by abrasive particles	Grooves
Adhesive	Metal transfer is the prime symptoms	Seizure, catering rough and torn-out surfaces.
Erosion	Presence of abrasives in the fast moving fluid and short abrasion furrows	Waves and troughs.
Corrosion	Presence of metal corrosion products.	Rough pits or depressions.
Fatigue	Presence of surface or subsurface cracks accompanied by pits and spalls	Sharp and angular edges around pits.
Impacts	Surface fatigue, small sub micron particles or formation of spalls	Fragmentation, peeling and pitting.
Delamination	Presence of subsurface cracks parallel to the surface with semi-dislodged or loose flakes	Loose, long and thin sheet like particles
Fretting	Production of voluminous amount of loose debris	Roughening, seizure and development of oxide ridges
Electric attack	Presence of micro craters or a track with evidence of smooth molten metal	Smooth holes

Literature available on the rate controlling wear mechanism demonstrated that it may change abruptly from one another at certain sliding velocities and contact loads, resulting in abrupt increases in wear rates. The conflicting results in the wear literature arise partly because of the differences in testing conditions, but they also make clear that a deeper understanding of the wear mechanism is required if an improvement in the wear resistances of the metal matrix composites is to be achieved. This in turn requires a systematic study of the wear under different stresses, velocities and temperatures. It is generally recognized that wear is a characteristic of a system and influenced by many parameters. Laboratory scale investigation if designed properly allows careful control of the tribo system where by the effects of different variables on wear behaviour of MMCs can be isolated and determined. The data generated through such investigation under controlled conditions may help in correct interpretation of the results.

In the present work studies have been carried out to assess the Friction and Wear behaviour of Al-red mud composite under controlled laboratory condition. A comprehensive picture of wear under different working conditions has been presented by conducting laboratory tests in pure sliding mode using a pin-on-disc machine and studying them under optical microscope to know the wear mechanism.

3.6 EXPERIEMENTS

Pin-on-Disc wear testing machine

Experiments have been conducted in the Pin-on-disc type Friction and Wear monitor (DUCOM; TL-20) with data acquisition system, (Fig. 3.5) which was used to evaluate the wear behaviour of the composite, against hardened ground steel disc (En-32) having hardness 65 HRC and surface roughness (R_a) 0.5 µm. It is versatile equipment designed to study wear under sliding condition only. Sliding generally occurs between a stationary Pin and a rotating disc. The disc rotates with the help of a D.C. motor; having speed range 0-2000 rev/min with wear track diameter 50 mm-180 mm, which could yield sliding speed 0 to 10 m/sec. Load is to be applied on pin (specimen) by dead weight through pulley string arrangement. The system has a maximum loading capacity of 200N.

3.6.1 EXPERIEMENTAL ASPECTS

MATERIALS USED

Aluminium

Commercially pure aluminium of IE–07 grades from National Aluminium Company (NALCO), Angul of Orissa was collected and was used for experimental purpose. The composition analysis along with other test results such as hardness, density, & tensile strength are presented in table-3.4 and 3.5.

Table – 3.4

Compositional analysis of aluminium

Sl.No	Si	Fe	Ti	V	Cu	Mn	Al
1	0.08	0.15	0.001	0.007	0.001	0.003	99.76

Table – 3.5

Density, Hardness & Tensile Strength of Aluminium

Density	2.7 gm/cc
Hardness	40.8 VHN
Tensile strength	67 MPa

Red mud

The red mud used for the present investigation was brought from the aluminum refinery of NALCO located at Damanjodi, Koraput, Orissa. Dust was prepared manually. The size of the dust was measured by using a sieve. As per this analysis the average size of the dust was 150 micron. Red mud dust was subjected to XRD, and chemical analysis. The presence of different elements as confirmed by chemical analysis is presented in table - 3.6.

XRD Results for red mud

XRD analysis was done to detect the presence of different elements in the red mud. XRD work was carried out on a Philips X-ray diffractometer. The X-ray diffractograms are taken using Cu Kα radiation at scan speed of 3^0 / min. Fig.3.6 shows the XRD analysis of red mud particles. The large peak found are of Al_2O_3 particles, where as small peaks indicates the presence of Fe_2O_3 in red mud. The noisy peaks indicate the presence of other trace elements like SiO_2, Al_3Fe etc.

XRD Results for composite

The selected 20% red mud added sample has been analyzed by x-ray diffraction analysis. The composites were produced under different conditions to identify the different phases in it; the study was made on the analysis chart, which is shown in the diffractogram Fig.3.7. The large peaks found are of Al_2O_3 particles, where as small peaks indicate the presence of FeO, and Al_3Fe in MMC. The noisy peaks indicate the presence of other trace elements like SiO_2 in the diagram and confirm the presence of red mud particles in the composites. The other particles presents in MMCs are very small peaks.

3.6.2 Preparation for the test specimens

Treatment of aluminium ingot

The cut pieces from ingot were pickled in 10% sodium hydroxide solution at 95-100^0C for 10 minutes. The sinut formed was removed by immersion for one minute in a mixture of one part nitric acid and one part water followed by washing in methanol. Immediately after drying in air, the weighted quantity of pickled aluminium was melted in a crucible.

Preparation of red mud

The required quantities of red mud (10, 15, 20 and 30 percent by weight) were taken in powder containers. The red mud was preheated in a furnace up to 400^oC and maintained at that temperature before mixing with Aluminum melt.

Melting and casting of test specimen

The weighted quantity of pickled aluminium were melted to desired superheating temperature of 800^0C in graphite crucible 3 phase electrical resistance furnace with temperature controlling device was used for melting. After melting was over, the required quantity of red mud particulates, preheated to around 400^0C were then added to the molten metal and stirred continuously by using mechanical stirrer. The stirring time was maintained between 60-80 seconds at an impeller speed of 550 rpm. During stirring to enhance the wettability small quantities of Magnesium was added to the melt [73]. The melt with the reinforced particulates were then poured to a prepared cylindrical mould by bottom pouring method. After pouring is over the melt was allowed to cool and solidify in the mould. For the purpose of comparison, the matrix material was also cast under similar processing conditions.

After solidification the casting were taken out from the mould and were cut to required shape and sizes for wear testing. To ascertain the distribution of reinforcement particulates cut pieces of the samples were polished and were inspected under optical microscope. The distribution with different volume fraction of red mud particles in the matrix are shown in Figs. 3.8. It is clear from these figures that the reinforcing particles were distributed uniformly in the aluminium matrix.

3.6.3 Testing of mechanical properties

Hardness test

The hardness of the heat treated samples was measured using a Leitz Wetzlar Germant-088303, Vickers micro hardness measuring machine with a load of 0.4903 N. The load was applied for 30 seconds. In order to eliminate possible segregation effect a minimum of three hardness readings were taken for each specimen at different locations of the test samples. The hardness so obtained is presented in table - 3.7.

Tensile test

The tensile behaviour of all the prepared samples were determined to examine the possibility of correlations between wear and tensile properties. Circular cross section specimen with a specific gauge length of 60 mm, grip distance of 100 mm and a gauge diameter of 8 mm were used for the tensile tests. These tests were carried out at a constant crosshead speed of 5 mm/min and full scale load range of 20 kN corresponding to an initial sample rate 9.103 pts/sec in an INSTRON-1195 tensile testing machine of 100 kN capacities. The results of the tensile tests for different composites are presented in table-3.7.

Impact test

The size of the specimen for the impact test was 10 mm x 10 mm x 50 mm with a rectangle notch size of 2 mm. The tests were carried out at room temperature using an impact-testing machine of Charpy type. The tests was carried out with an initial energy of hammer 30 Kg.m and with a striking velocity of 5.6 m/s. Impact test result for different test specimen are presented in table–3.7.

3.6.4 Determination of the amount of wear

Before conducting the test, the pin and the disc surfaces were polished with emery papers, so that the contact will be a smooth one. All the wear tests were carried out as per ASTM G-99 standard under unlubricated condition in a normal laboratory atmosphere at 50-60% relative humidity and a temperature of 28-32^{0}C. Each test was carried out for 6 hrs run. The mass loss in the specimen after each test was estimated by measuring the weight of the specimen before and after each test using an electronic weighing machine having accuracy up to 0.01mg. Care has been taken that the specimens under test are continuously cleaned with woolen cloth to avoid the entrapment of wear debris and to achieve uniformly in experiential procedure. The test pieces are cleaned with tetra-chloro-ethylene solution prior and after each test.

Wear Test

The tests have been carried out under the following conditions;

- The specimens under tests were fixed to the collect (Fig.3.5). The collect along with the specimen (Pin) is positioned at a particular track diameter. This track diameter is to be changed after each tests i.e. a fresh track is to be selected for each specimen. During experiment the specimens remains fixed and disc rotates.

- Load is applied through a dead weight loading system to press the pin against the disc.

- Frictional force arises at the contact can be read out from the controller.

- The speed of the disc or motor rpm can be varied through the controller.

- For a particular type of composite 27 sets of test pieces were tested.

- Each set of test was carried out for a period of 6 hrs run. After each one hour run the test pieces were removed from the machine and weighted accurately to determine the loss in weight.

Calculation

Wear rate was estimated by measuring the mass loss in the specimen after each test and mass loss, Δm in the specimen was obtained. Cares have been taken after each test to avoid entrapment of wear debris in the specimen. Wear rate which relates to the mass loss to sliding distance (L) was calculated using the expression,

$$W_r = \Delta m/L \qquad \text{------------------------------------} \qquad (3.1)$$

The volumetric wear rate W_v of the composite is relate to density (ρ) and the abrading time (t), was calculated using the expression,

$$W_v = \Delta m / \rho t \quad \text{--------------------------------} \quad (3.2)$$

The friction force was measured for each pass and then averaged over the total number of passes for each wear test. The average value of co-efficient of friction, μ of composite was calculated from the expression,

$$\mu = F_f / F_n \quad \text{--------------------------------} \quad (3.3)$$

Where F_f is the average friction force and F_n is the applied load.

For characterization of the abrasive wear behaviour of the composite, the specific wear rate is employed. This is defined as the volume loss of the composite per unit sliding distance and per unit applied normal load. Often the inverse of specific wear rate expresses in terms of the volumetric wear rate as

$$W_s = W_v / V_s F_n \quad \text{--------------------------------} \quad (3.4)$$

where V_s is the sliding velocity.

Experimental results of the wear test of different test pieces (10, 15, 20, and 30 % by weight of red mud) at different test conditions are tabulated and presented in table 3.8 to 3.52.

3.7 RESULTS AND DISCUSSION

Based on the tabulated results, various graphs are plotted and presented in Figs. 3.9 to 3.24 for different percentage of reinforcement under different test conditions.

Figs.3.9 to 3.11 shows the variation of wear rate with sliding distance for different loads (10N, 20N, 30N) at 200 rpm. It is seen from the plots that with addition of red mud particles the wear rate of the composite is decreasing. Also as the sliding distance increases the wear rate first decreases and then almost remains same for the entire test period. Since the trend for 300 and 400 rpm remains same as 200 rpm, it has not been presented here.

Figs. 3.12 to 3.14 shows the variation of specific wear rate with filler volume fraction i.e. red mud. It is clear from the plot that the specific wear rate decreases with increase in filler volume fraction and after attaining a minimum value within 10-20% it again increases. Thus there exists an optimum filler volume fraction, which gives maximum wear resistance to the composite.

Figs.3.15 to 3.17 shows variation of specific wear rate with sliding velocity. The plot shows that the specific wear rate of the composite increases with increase in sliding velocity. From the figure it is also clear that rate of increase of wear rate is initially high and decreases as the load increases. For 30% volume of red mud this is some what deviating in all cases i.e. the wear rate increases to a very high value in comparison to other. This deviation some what relates to the results projected in Figs. 3.12 to 3.14.

Figs. 3.18 to 3.20 shows the variation of volumetric wear rate with normal load. It can be observed from the plots that the volumetric wear rate increases with increase in normal load. This is because at higher load, the frictional thrust increases, which results in increased debonding and fracture. A similar effect of normal load on volumetric wear rate has been observed by Cirino et.al. [189] in the case of carbon epoxy composite and Verma et. al. [190] for GRP composite. It is also evident from the plot that at higher speed and high volume fraction, the volumetric wear rate of the composite for a load of 20 N is higher than pure aluminium. This shows the dependence of load and the volume fraction of red mud on the volumetric wear behaviour of the composite over pure aluminium. At 400 rpm (i.e. velocity, v_s = 3.141 m/sec) the critical load (the load above which the composite shows higher volumetric wear rate than pure aluminium) was reduced to 20 N.

As many parameters e.g. sliding velocity, sliding distance and load are responsible for wear and are expressed in the earlier figures, it is more appropriate to express the sliding wear results in terms of the wear constant, K [191,192] as extracted from Archard's law. For known values of V (wear volume), H (Vickers hardness of the softer material), S (sliding distance), and L (normal load), the wear coefficient (K) can be determined from the following equations:

$$V = K\,L\,S / H \qquad \text{---------------------------} \qquad (3.5)$$

Rabinowicz interpreted the wear constant K as a co-efficient related to the probability of asperity fracture [193]. Thus the wear constant K is a correlation factor between several variables of the sliding wear experimental results and is related to various microscopic mechanisms. Fig 3.21 shows the variation of wear co-efficient with particle volume content. It is apparent in this figure that the wear co-efficient tends to decrease with increasing particle volume content. Thus red mud addition is beneficial in reducing the wear of the aluminium red mud composite. Same type of results has been reported by S.C.Tjong et.al. [54] for the wear behaviour of aluminium based MMC composite reinforced with a preform aluminosilicate fiber.

Figs. 3.22 to 3.24 shows the variation of coefficient of friction with normal load. This shows that the coefficient of friction in all cases decreases with the increase of normal load. This decrease in value occurs likely as a result of particulate standing above the surface making contacting area of the specimen smaller.

3.8 Micro structural Observation

The worn-out surface of some selected /typical specimens after the wear test are observed under optical microscope Figs. 3.25, (a-c) shows the surface morphology of aluminium 10% red mud composite, tested under two different load and speed conditions . When the sample is tested at slow speeds i.e. at sliding velocity of 300 rpm, Fig. 3.25 (a), it appears that cavities are formed in the composite matrix and have aligned parallel to the direction of sliding. Some particles also have chopped off during sliding. With increase in sliding velocity i.e. at 400 rpm, Fig. 3.25 (b), worn surface shows a different appearance. The amount of cavitations is less than that of the previous case. In some regions, the substructures are aligned parallel to the sliding direction. In some area smaller particulate have come out from the composite matrix. For the same composite, at same sliding speed of 400 rpm and with increasing applied load i.e. from 20 N to 30 N, cracks have appeared and are propagated in different direction. These might have help in chipping of hard particles i.e. red mud. In case of aluminium-15% red mud composite tested with sliding velocity of 300 and 400 rpm, are shown in Figs.3.26, (a) and (b) respectively. From the Figs. it can be seen that with increasing the sliding velocity grooves have appeared [Fig.3.26 (b)] where as at lower speeds, wave types structures is observed [Fig.3.26 (a)].

The structures of the worn surfaces are greatly dependent on sliding speed and applied load conditions [194]. The surface structures of the samples (Al+20% RM) are shown in Figs.3.27 (a-e). Comparing these figures it can be visualized that when the sample is rubbed, against steel wheel, at low sliding speed and low applied load hard particles might have chipped off and the aluminium grains are grown into bigger sizes with increase in applied load i.e. from 10 N to 30 N, [(Figs.3.27, (b) and (c)], the aluminium matrix appears to be smeared along the direction of the sliding. Amount of cavitations also have increased. Some cavities appear to be formed around the hard particles, (i.e. red mud particulates). For the same composite the worn surfaces obtained at higher sliding velocity, (i.e.400 rpm), for two different applied load (i.e.10 N and 20 N) are shown in Figs. 3.27 (d) and (e) respectively. The worn surfaces are relatively smoother than that at lower sliding speeds [Figs. 3.27 (a) and (b)]. It may be noted that cracks are formed parallel to the sliding direction. When the applied load is less/small, fracture/fragmentation/motion of hard particles (i.e. red mud) occurs along the crack lines. With increase in applied load although the amount of cavitations appears to be low but deep cracks and grooves are clearly visible [Fig. 3.27 (e)].

It has been observed that during sliding hard particulate erode the steel counter face and forms a very thin layer of oxidized iron which acts as a lubricant therefore the change in this structural appearance is observed [195]. Hard particles at grain boundaries would lead to less amount of particulate breakage. Large plastics strains can arise in the composite matrix coming into direct contact with the steel counter face leads to subsurface crack propagation and subsurface delamination [196]. From the micrograph [Figs.3.27 (a-c], it is seen that some cracks are formed/originated at the grain boundaries of aluminium. This might be due to [194] strain hardening of aluminium during sliding with a applied load and due to pulling up of hard phase particles i.e. red mud from the aluminium grain boundaries [195]. With increasing the applied load this effect is more pronounced [Fig.3.3 (c)]. This might have been caused also due to embrittlement of hard particles during sliding.

3.9 CONCLUSIONS

The following conclusions have been drawn from the above study

- Aluminium matrix composites have been successfully fabricated with fairly uniform distribution of red mud particles.

- Dispersion of red mud particles in aluminium matrix improves the hardness of the matrix material and also the wear behaviour of the composite. The effect is the increase in interfacial area between aluminium matrix and red mud particles leading to the increase in strength appreciably.

- Co-efficient of friction decreases as the load increases.

- At higher load and higher speed specific wear rate decreases with increases in Red mud content.

- Wear co-efficient tends to decrease with increasing particle volume content. It also indicates that red mud addition is beneficial in reducing wear of the aluminium red mud composite.

- Wear resistance of the composite increases due to addition of red mud particles. However there exists an optimum filler volume friction which gives maximum wear resistance to the composite.

Table – 3.6

Chemical (dry) analysis of red mud

Constituents	% (wt)	Constituents	% (wt)
Al_2O_3	15.0	Fe_2O_3	54.8
TiO_2	3.7	SiO_2	8.44
Na_2O	4.8	CaO	2.5
P_2O_5	0.67	V_2O_5	0.38
Ga_2O_3	0.096	Mn	1.1
Zn	0.018	Mg	0.056
Organic C	0.88	L.O.I	Balance

Table - 3.7

Mechanical properties of specimens

Specimen	Yield Stress (MPa)	Ultimate Stress (MPa)	Modulus of Elasticity (GPa)	Percentage Elongation	Impact Strength (Kg.m/cm^2)	Hardness (VHN)
Pure Al	24.5	67	73	25	6.3	40.8
90% Al + 10% RM	23.47	6.75	34.98	9.23	7.44	52.78
85% Al + 15% RM	31.77	7.68	47.53	11.51	8.98	53.6
80% Al + 20% RM	25.83	5.83	42.1	14.18	8.34	55.8
70% Al + 30% RM	31.96	7.1	57.1	16.15	10.66	54.82

Table– 3.8

Aluminium Load – 10 N $\rho = 2.62 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.25	8.18	0.07	3600	0.33	0.33	4.53	0.15175	7.4215	6.018
8.25	8.12	0.13	7200	0.33	0.33	9.06	0.14091	6.8914	5.5886
8.25	8.04	0.21	10800	0.29	0.29	13.59	0.15175	7.4215	6.0185
8.25	7.97	0.28	14400	0.33	0.33	18.12	0.15175	7.4215	6.0185
8.25	7.92	0.33	18000	0.30	0.30	22.65	0.14308	6.997	5.674
8.25	7.87	0.38	21600	0.33	0.33	27.18	0.1373	6.714	5.444

Table – 3.9

Aluminium Load – 10 N $\rho = 2.62 \times 10^3$ Kg/m^3

RPM = 300 Vs = 1.885 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.00	7.88	0.12	3600	0.33	0.33	6.786	0.1734	12.722	6.87
8.00	7.79	0.21	7200	0.32	0.32	13.572	0.1445	10.602	5.733
8.00	7.71	0.29	10800	0.33	0.33	20.358	0.1397	10.25	5.543
8.00	7.64	0.36	14400	0.33	0.33	27.144	0.130	9.542	5.16
8.00	7.56	0.44	18000	0.34	0.34	33.930	0.1272	9.33	5.045
8.00	7.47	0.53	21600	0.34	0.34	40.716	0.1276	9.365	5.064

Table – 3.10

Aluminium, Load – 10 N $\rho = 2.62 \times 10^3$ Kg/m^3

RPM = 400 Vs = 3.141 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.77	7.57	0.20	3600	0.49	0.49	11.309	0.1731	21.204	6.882
7.77	7.49	0.28	7200	0.31	0.31	22.618	0.1215	14.843	4.817
7.77	7.37	0.40	10800	0.47	0.47	33.927	0.1157	14.136	4.586
7.77	7.19	0.58	14400	0.47	0.47	45.236	0.1257	15.373	4.989
7.77	6.99	0.78	18000	0.43	0.43	56.545	0.1353	16.539	5.367
7.77	6.87	0.90	21600	0.38	0.38	67.854	0.1301	15.903	5.161

Table – 3.11

Aluminium Load – 20 N $\rho = 2.62 \times 10^3$ Kg/m^3

RPM = 200 Vs =1.257 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.85	7.69	0.16	3600	0.5	0.25	4.530	0.3469	16.96	6.877
7.85	7.57	0.28	7200	0.54	0.27	9.06	0.3035	14.84	6.017
7.85	7.49	0.36	10800	0.6	0.3	13.59	0.2601	12.72	5.158
7.85	7.42	0.43	14400	0.58	0.29	18.12	0.233	11.397	4.622
7.85	7.34	0.51	18000	0.58	0.29	22.65	0.2211	10.814	4.385
7.85	7.27	0.58	21600	0.54	0.27	27.18	0.2096	10.249	4.156

Table – 3.12

Aluminium Load – 20 N $\rho = 2.62 \times 10^3$ Kg/m^3

RPM = 300 Vs =1.885 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.51	7.29	0.22	3600	0.54	0.27	6.786	0.318	23.320	6.305
7.51	7.17	0.34	7200	0.66	0.33	13.572	0.245	18.023	4.873
7.51	7.06	0.45	10800	0.64	0.32	20.358	0.216	15.903	4.300
7.51	6.94	0.59	14400	0.70	0.35	27.144	0.213	15.638	4.228
7.51	6.78	0.73	18000	0.58	0.29	33.930	0.211	15.479	4.185
7.51	6.58	0.93	21600	0.6	0.3	40.716	0.224	16.433	4.443

Table – 3.13

Aluminium Load – 20 N $\rho = 2.62 \times 10^3$ Kg/m^3

RPM = 400 Vs =3.141 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.29	7.99	0.30	3600	0.44	0.22	11.309	0.260	31.81	5.161
8.29	7.71	0.58	7200	0.40	0.20	22.618	0.251	30.74	4.988
8.29	7.37	0.92	10800	0.26	0.13	33.927	0.266	32.51	5.275
8.29	7.97	1.32	14400	0.92	0.46	45.236	0.286	34.98	5.676
8.29	7.67	1.62	18000	1.08	0.54	56.545	0.281	34.35	5.676
8.29	7.42	1.87	21600	0.94	0.47	67.854	0.279	33.04	5.419

Table – 3.14

Aluminium Load – 30 N $\rho = 2.62 \text{ x } 10^3$ Kg/m^3

RPM = 200 Vs =1.257 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.09	7.88	0.21	3600	0.69	0.23	4.530	0.455	22.26	6.076
8.09	7.72	0.37	7200	0.48	0.16	9.06	0.401	19.61	5.30
8.09	7.59	0.50	10800	0.72	0.24	13.59	0.361	17.67	4.771
8.09	7.49	0.60	14400	0.78	0.26	18.12	0.325	15.90	4.291
8.09	7.40	0.69	18000	0.75	0.25	22.65	0.299	14.631	3.96
8.09	7.33	0.76	21600	0.69	0.23	27.18	.0.275	13.43	3.63

Table – 3.15

Aluminium Load – 30 N $\rho = 2.62 \text{ x} 10^3$ Kg/m^3

RPM = 300 Vs =1.885 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.74	7.49	0.25	3600	0.51	0.17	6.786	0.361	26.50	4.776
7.74	7.32	0.42	7200	0.60	0.20	13.572	0.303	22.26	4.012
7.74	7.10	0.64	10800	0.63	0.21	20.358	0.308	22.61	4.075
7.74	6.75	0.99	14400	0.81	0.27	27.144	0.357	26.24	4.730
7.74	6.45	1.29	18000	0.54	0.18	33.930	0.372	27.35	4.930
7.74	6.20	1.54	21600	0.6	0.20	40.716	0.371	27.21	4.900

Table – 3.16

Aluminium Load – 30 N $\rho = 2.62 \times 10^3$ Kg/m^3

RPM = 400 Vs =3.141m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.35	7.96	0.39	3600	0.72	0.24	11.309	0.3368	41.34	4.472
8.35	7.68	0.67	7200	0.69	0.23	22.618	0.2906	35.51	3.841
8.35	7.37	0.98	10800	0.90	0.30	33.927	0.2834	34.632	3.746
8.35	6.92	1.43	14400	0.87	0.29	45.236	0.3101	37.902	4.10
8.35	6.58	1.77	18000	1.02	0.34	56.545	0.3071	37.531	4.06
8.35	6.33	2.02	21600	0.84	0.28	67.854	0.2920	35.694	3.861

Table – 3.17

Al+10%RM Load – 10 N $\rho = 2.47 \times 10^3$ Kg/m^3

RPM = 200 Vs =1.257m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.40	8.36	0.04	3600	0.33	0.33	4.53	0.0867	4.498	3.647
8.40	8.33	0.07	7200	0.31	0.31	9.06	0.07587	3.936	3.191
8.40	8.29	0.11	10800	0.34	0.34	13.59	0.0795	4.123	3.343
8.40	8.25	0.15	14400	0.28	0.28	18.12	0.0813	4.2173	3.42
8.40	8.20	0.20	18000	0.33	0.33	22.65	0.0867	4.4984	3.648
8.40	8.13	0.27	21600	0.32	0.32	27.18	0.0831	4.311	3.496

Table – 3.18

Al+10%RM Load – 10 N $\rho = 2.47 \times 10^3$ Kg/m^3

RPM = 300 Vs =1.885m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.46	8.39	0.07	3600	0.33	0.33	6.786	0.1012	7.872	4.257
8.46	8.24	0.12	7200	0.31	0.31	13.572	0.0867	6.747	3.648
8.46	8.30	0.16	10800	0.34	0.34	20.358	0.077	5.997	3.243
8.46	8.23	0.23	14400	0.28	0.28	27.144	0.0831	6.466	3.496
8.46	8.16	0.30	18000	0.33	0.33	33.930	0.08674	6.748	3.649
8.46	8.08	0.38	21600	0.32	0.32	40.716	0.09156	7.1225	3.8517

Table – 3.19

Al+10%RM Load – 10 N $\rho = 2.47 \times 10^3$ Kg/m^3

RPM = 400 Vs =3.141m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.25	8.15	0.10	3600	0.47	0.47	11.309	0.0801	11.24	3.647
8.25	8.07	0.18	7200	0.55	0.55	22.618	0.7808	10.82	3.284
8.25	7.93	0.32	10800	0.56	0.56	33.927	0.0925	11.99	3.891
8.25	7.83	0.42	14400	0.55	0.55	45.236	0.0919	11.8	3.829
8.25	7.70	0.55	18000	0.53	0.53	56.545	0.0954	12.37	4.014
8.25	7.50	0.75	21600	0.59	0.59	67.854	0.1084	14.05	4.559

Table – 3.20

Al+10%RM Load – 20 N $\rho = 2.47 \times 10^3$ Kg/m^3

RPM 200 Vs =1.257m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.52	7.40	0.12	3600	0.54	0.27	4.53	0.261	13.49	5.469
7.52	7.35	0.17	7200	0.44	0.22	9.06	0.184	9.55	3.872
7.52	7.29	0.23	10800	0.48	0.24	13.59	0.166	8.62	3.495
7.52	7.20	0.32	14400	0.48	0.24	18.12	0.173	8.996	3.647
7.52	7.12	0.40	18000	0.54	0.27	22.65	0.1734	8.996	3.647
7.52	7.04	0.48	21600	0.60	0.30	17.18	0.1734	8.996	3.647

Table – 3.21

Al +10%RM Load –20 N $\rho = 2.45 \times 10^3$ Kg/m^3

RPM = 300 Vs = 1.885 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.06	7.94	0.12	3600	0.76	0.38	6.786	0.1734	13.49	3.647
8.06	7.88	0.18	7200	0.70	0.35	13.572	0.1301	10.12	2.736
8.06	7.82	0.24	10800	0.76	0.38	20.358	0.1156	8.99	2.43
8.06	7.76	0.30	14400	0.80	0.40	27.144	0.1084	8.43	2.28
8.06	7.70	0.36	18000	0.78	0.39	33.93	0.1084	8.097	2.189
8.06	7.64	0.42	21600	0.76	0.38	40.716	0.1012	7.872	2.129

Table –3.22

Al +10%RM Load – 20 N $\rho = 2.47 \times 10^3$ Kg/m^3

RPM = 400 Vs = 3.141m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.11	7.91	0.2	3600	0.56	0.28	11.309	0.173	22.49	3.649
8.11	7.75	0.36	7200	0.74	0.37	22.618	0.1561	20.24	3.284
8.11	7.47	0.64	10800	0.68	0.34	33.927	0.185	23.99	3.829
8.11	7.15	0.96	14400	0.68	0.34	45.236	0.2082	26.99	4.379
8.11	7.87	1.24	18000	0.66	0.33	56.545	0.2151	27.89	4.525
8.11	7.67	1.44	21600	0.64	0.32	67.8540	0.02083	26.99	4.379

Table – 3.23

Al +10%RM Load – 30 N $\rho = 2.47 \times 10^3$ Kg/m^3

RPM = 200 Vs =1.257m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.15	8.00	0.15	3600	0.63	0.21	4.53	0.3251	16.86	4.557
8.15	7.84	0.31	7200	0.66	0.22	9.06	0.336	17.43	4.711
8.15	7.75	0.4	10800	0.48	0.16	13.59	0.289	14.99	4.052
8.15	7.63	0.52	14400	0.66	0.22	18.12	0.281	14.612	3.949
8.15	7.50	0.65	18000	0.54	0.18	22.65	0.282	14.62	3.95
8.15	7.40	0.75	21600	0.63	0.21	27.18	0.271	14.05	3.79

Table – 3.24

Al+10%RM Load – 30 N $\rho = 2.47 \times 10^3$ Kg/m^3

RPM = 300 Vs =1.885 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.19	7.99	0.20	3600	0.54	0.18	6.786	0.2891	22.492	4.050
8.19	7.90	0.29	7200	0.63	0.21	13.572	0.2096	16.301	2.938
8.19	7.80	0.39	10800	0.54	0.18	20.358	0.1879	14.619	2.633
8.19	7.65	0.54	14400	0.54	0.18	27.144	0.1951	15.182	2.736
8.19	7.55	0.64	18000	0.54	0.18	33.93	0.185	14.39	2.593
8.19	7.48	0.71	21600	0.51	0.17	40.716	0.171	13.30	2.397

Table – 3.25

Al+10%RM Load – 30 N $\rho = 2.47 \times 10^3$ Kg/m^3

RPM = 400 Vs =3.141 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.80	7.55	0.25	3600	0.93	0.31	11.309	0.2168	28.155	3.039
7.80	7.37	0.43	7200	0.81	0.27	22.618	0.1865	24.179	2.607
7.80	7.17	0.63	10800	0.90	0.30	33.927	0.1821	23.616	2.553
7.80	6.83	0.97	14400	0.96	0.32	45.236	0.2103	27.271	2.953
7.80	6.59	1.21	18000	0.84	0.28	56.545	0.209	27.215	2.942
7.80	6.39	1.41	21600	0.96	0.32	67.854	0.203	26.428	2.855

Table –3.26

Al + 15 %RM   Load – 10 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200   Vs =1.257 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	W_r ×10^{-6} (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.88	7.85	0.03	3600	0.47	0.47	4.53	0.0650	3.3467	2.714
7.88	7.82	0.06	7200	0.55	0.55	9.06	0.0650	3.3467	2.714
7.88	7.78	0.10	10800	0.56	0.56	13.59	0.0723	3.7185	3.0155
7.88	7.75	0.13	14400	0.55	0.55	18.12	0.0705	3.6256	2.940
7.88	7.70	0.18	18000	0.53	0.53	22.65	0.0780	4.0161	3.2568
7.88	7.67	0.21	21600	0.59	0.59	27.18	0.0759	3.9045	3.1663

Table – 3.27

Al + 15 %RM   Load – 10 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 300   Vs =1.885 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	W_r × 10^{-6} (N/m)	Wv × 10^{-12} (m^3/sec)	Ws ×10^{-13} (m^3/N-m)
8.02	7.97	0.05	3600	0.36	0.36	6.786	0.0722	5.577	3.051
8.02	7.91	0.11	7200	0.34	0.34	13.572	0.0795	6.135	3.317
8.02	7.88	0.14	10800	0.36	0.36	20.358	0.0674	5.206	2.812
8.02	7.85	0.17	14400	0.26	0.26	27.144	0.0614	4.741	2.541
8.02	7.81	0.21	18000	0.36	0.36	33.93	0.0671	4.685	2.531
8.02	7.78	0.24	21600	0.37	0.37	14.716	0.0578	4.462	2.521

Table – 3.28

Al + 15 %RM Load – 10 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM =400 Vs =3.141 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.70	7.58	0.12	3600	0.36	0.36	11.309	0.1041	13.38	4.348
7.70	7.41	0.29	7200	0.34	0.34	22.618	0.1257	16.17	5.257
7.70	7.21	0.49	10800	0.36	0.36	33.927	0.1417	18.22	5.906
7.70	7.04	0.66	14400	0.26	0.26	45.236	0.1431	18.40	5.971
7.70	6.90	0.80	18000	0.36	0.36	56.545	0.1388	17.849	5.792
7.70	8.85	0.85	21600	0.37	0.37	67.875	0.1229	15.801	5.127

Table – 3.29

Al + 15 %RM Load – 20 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM =200 Vs =1.257m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.78	7.69	0.09	3600	0.36	0.36	4.53	0.195	10.041	4.091
7.78	7.64	0.14	7200	0.34	0.34	9.06	0.151	7.809	3.166
7.78	7.60	0.18	10800	0.36	0.36	13.59	0.130	6.693	2.712
7.78	7.54	0.24	14400	0.26	0.26	18.12	0.130	6.693	2.712
7.78	7.49	0.29	18000	0.36	0.36	22.65	0.125	6.470	2.623
7.78	7.46	0.32	21600	0.37	0.37	27.18	0.115	5.949	2.408

Table – 3.30

Al + 15 %RM　　　Load – 20 N　　　$\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 300　　　Vs =1.885m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.95	7.85	0.10	3600	0.54	0.27	6.786	0.1445	11.15	3.014
7.95	7.73	0.22	7200	0.66	0.33	13.572	0.159	12.27	3.317
7.95	7.58	0.37	10800	0.72	0.36	20.348	0.1783	13.758	3.72
7.95	7.41	0.54	14400	0.70	0.35	27.144	0.1952	15.06	4.072
7.95	7.23	0.72	18000	0.66	0.33	33.93	0.2082	16.064	4.344
7.95	7.04	0.91	21600	0.72	0.36	40.716	0.2193	16.92	4.575

Table – 3.31

Al + 15 %RM　　　Load – 20N　　　$\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 400　　　Vs =3.141m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.73	7.61	0.12	3600	0.68	0.34	11.208	0.1041	13.381	2.171
7.73	7.44	0.29	7200	0.66	0.33	22.618	0.1257	16.178	2.625
7.73	7.24	0.49	10800	0.84	0.42	33.927	0.1417	18.221	2.953
7.73	6.89	0.84	14400	0.88	0.44	45.236	0.156	23.427	3.801
7.73	6.65	1.08	18000	0.78	0.39	56.545	0.187	18.741	3.044
7.73	6.45	1.28	21600	0.72	0.36	67.854	0.192	23.798	3.864

Table – 3.32

Al + 15 %RM   Load – 30 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200   Vs =1.257m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.08	7.96	0.12	3600	0.45	0.15	4.53	0.261	13.338	3.616
8.08	7.85	0.23	7200	0.72	0.24	9.06	0.249	12.829	3.468
8.08	7.72	0.36	10800	0.54	0.18	13.59	0.260	13.386	3.618
8.08	7.58	0.50	14400	0.45	0.15	18.12	0.271	13.945	3.77
8.08	7.46	0.62	18000	0.51	0.17	22.60	0.269	13.833	3.74
8.08	7.38	0.70	21600	0.57	0.19	27.18	0.253	13.015	3.518

Table – 3.33

Al + 15 %RM   Load – 30 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM 300   Vs =1.885m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.11	7.81	0.30	3600	0.78	0.26	6.786	1.879	14.51	2.612
8.11	7.61	0.50	7200	0.75	0.25	13.572	0.361	27.88	5.025
8.11	7.51	0.60	10800	0.39	0.13	20.358	0.289	22.31	4.021
8.11	7.41	0.70	14400	0.45	0.15	27.144	0.252	19.522	3.519
8.11	7.34	0.77	18000	0.48	0.16	33.13	0.222	15.61	2.812
8.11	7.29	0.82	21600	0.42	0.14	40.716	0.197	15.24	2.747

Table – 3.34

Al + 15 %RM Load – 30 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 400 Vs = 3.141 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.46	8.20	0.26	3600	1.26	0.42	11.309	0.225	29.00	3.137
8.46	8.03	0.43	7200	1.14	0.38	22.618	0.186	23.98	2.594
8.46	7.82	0.64	10800	1.23	0.41	33.927	0.185	23.79	2.573
8.46	7.58	0.88	14400	0.96	0.32	45.236	0.191	24.59	2.654
8.46	7.33	1.16	18000	0.72	0.24	56.545	0.201	25.88	2.799
8.46	7.15	1.13	21600	0.87	0.29	67.855	0.163	21.01	2.271

Table – 3.35

Al + 20 % RM Load – 10 N $\rho = 2.527 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.47	8.43	0.04	3600	0.36	0.36	4.53	0.0867	4.41	3.576
8.47	8.39	0.08	7200	0.34	0.34	9.06	0.0867	4.41	3.576
8.47	8.35	0.12	10800	0.36	0.36	13.59	0.0867	4.41	3.576
8.47	8.32	0.15	14400	0.26	0.26	18.12	0.0813	4.1336	3.352
8.47	8.30	0.17	18000	0.36	0.36	22.65	0.0737	3.7478	3.04
8.47	8.27	0.20	21600	0.37	0.37	27.18	0.0723	3.6743	2.98

Table –3.36

Al + 20 % RM   Load – 10 N $\rho = 2.52 \times 10^3$ Kg/m^3

RPM - 300   Vs = 1.885 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.33	8.29	0.04	3600	0.36	0.36	6.786	0.0578	4.41	2.384
8.33	8.27	0.06	7200	0.34	0.34	13.572	0.043	3.31	1.789
8.33	8.23	0.10	10800	0.36	0.36	20.358	0.048	3.67	1.986
8.33	8.18	0.15	14400	0.26	0.26	27.144	0.054	4.13	2.23
8.33	8.15	0.18	18000	0.36	0.36	33.93	0.05	3.96	2.14
8.33	8.13	0.20	21600	0.37	0.37	40.716	0.048	3.67	1.984

Table – 3.37

Al + 20 % RM   Load – 10 N $\rho = 2.52 \times 10^3$ Kg/m^3

RPM = 400   Vs = 3.141 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.10	7.84	0.16	3600	0.36	0.36	11.309	0.138	17.636	5.723
8.10	7.64	0.36	7200	0.34	0.34	22.618	0.156	19.841	6.439
8.10	7.45	.0.55	10800	0.36	0.36	33.927	0.159	20.208	6.558
8.10	7.32	0.68	14400	0.26	0.26	45.236	0.147	18.738	6.081
8.10	7.13	0.87	18000	0.36	0.36	56.545	0.151	14.991	4.864
8.10	6.93	1.07	21600	0.37	0.37	67.857	0.154	19.657	6.379

Table - 3.38

Al + 20 % RM Load – 20 N $\rho = 2.52 \times 10^3$ Kg/m^3

RPM = 200 Vs =1. 257 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.73	7.66	0.07	3600	0.38	0.19	4.53	0.1517	7.716	3.128
7.73	7.67	0.12	7200	0.36	0.18	9.06	0.130	6.613	2.681
7.73	7.55	0.18	10800	0.38	0.19	13.59	0.1301	6.613	2.681
7.73	7.48	0.25	14400	0.52	0.26	18.12	0.1354	6.889	2.793
7.73	7.44	0.29	18000	0.50	0.25	22.65	0.1257	6.393	2.592
7.73	7.37	0.36	21600	0.56	0.28	27.16	0.130	6.613	2.681

Table - 3.39

Al + 20 % RM Load – 20 N $\rho = 2.52 \times 10^3$ Kg/m^3

RPM = 300 Vs = 1.885 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$	Ws $\times 10^{-13}$ (m^3/N-m)
7.85	7.70	0.15	3600	0.70	0.35	6.786	0.2168	16.53	4.469
7.85	7.52	0.33	7200	0.68	0.34	13.572	0.238	18.187	4.917
7.85	7.28	0.47	10800	0.90	0.45	20.358	0.226	17.26	4.666
7.85	7.00	0.85	14400	0.68	0.34	27.145	0.307	23.42	6.332
7.85	6.73	1.12	18000	0.66	0.33	33.93	0.323	24.69	6.675
7.85	6.50	1.35	21600	0.76	0.38	40.716	0.325	24.81	6.708

Table – 3.40

Al + 20 % RM Load 20 N $\rho = 2.52 \times 10^3$ Kg/m^3

RPM = 400 Vs =3.141m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.93	7.62	0.31	3600	0.72	0.36	11.309	0.268	34.171	5.544
7.93	7.26	0.67	7200	0.76	0.38	22.618	0.291	36.926	5.991
7.93	6.82	1.11	10800	0.82	0.41	33.97	0.321	40.784	6.617
7.93	6.41	1.52	14400	0.76	0.38	45.236	0.329	41.887	6.796
7.93	5.89	2.04	18000	0.90	0.45	56.545	0.353	44.973	7.297
7.93	5.49	2.44	21600	0.80	0.40	67.854	0.352	44.826	7.273

Table – 3.41

Al + 20 % RM Load – 30 N $\rho = 2.62 \times 10^3$ Kg/m^3

RPM = 200 Vs =1.257 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.34	8.24	0.10	3600	0.60	0.20	4.53	0.216	11.022	2.979
8.34	8.10	0.24	7200	0.45	0.15	9.06	0.260	13.227	3.575
8.34	7.90	0.44	10800	0.63	0.21	13.59	0.318	16.166	4.369
8.34	7.83	0.51	14400	0.39	0.13	18.12	0.276	14.054	3.791
8.34	7.79	0.55	18000	0.45	0.15	22.65	0.238	12.125	3.277
8.34	7.78	0.56	21600	0.33	0.11	27.18	0.208	10.288	2.781

Table – 3.42

Al + 20 % RM   Load – 30 N $\rho = 2.52 \times 10^3$ Kg/m^3

RPM = 300   Vs =1.885m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.27	8.07	0.20	3600	0.66	0.22	6.786	0.2891	22.04	3.975
8.27	7.95	0.32	7200	0.81	0.27	13.572	0.2313	17.63	3.179
8.27	7.84	0.43	10800	0.87	0.29	20.358	0.2072	15.79	2.846
8.27	7.72	0.55	14400	0.87	0.29	27.144	0.1988	15.19	2.731
8.27	7.66	0.61	18000	0.75	0.253	33.92	0.1764	13.44	2.423
8.27	7.62	0.65	21600	0.84	0.28	40.716	0.1566	11.95	2.15

Table – 3.43

Al + 20 % RM   Load – 30 N $\rho = 2.52 \times 10^3$ Kg/m^3

RPM = 400   Vs = 3.141m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.96	7.61	0.35	3600	0.78	0.26	11.309	0.3036	38.58	4.173
7.96	7.37	0.59	7200	0.90	0.30	22.618	0.2559	32.517	3.517
7.96	7.13	0.83	10800	0.78	0.26	33.927	0.2400	30.496	3.299
7.96	6.81	1.15	14400	0.69	0.23	45.236	0.2565	31.691	3.428
7.96	6.53	1.43	18000	0.72	0.24	56.945	0.2481	31.525	3.410
7.96	6.33	1.63	21600	0.75	0.25	67.854	0.2356	29.94	3.238

Table – 3.44

Al + 30 % RM Load – 10 N $\rho = 2.55 \times 10^3$ Kg/m^3

RPM = 200 Vs =1. 257m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.45	8.40	0.05	3600	0.36	0.36	4.53	0.1083	5.446	4.416
8.45	8.38	0.07	7200	0.34	0.34	9.06	0.0759	3.812	3.091
8.45	8.34	0.11	10800	0.36	0.36	13.59	0.0794	3.994	3.238
8.45	8.33	0.12	14400	0.26	0.26	18.12	0.0668	3.267	2.649
8.45	8.30	0.15	18000	0.36	0.36	22.65	0.065	3.267	2.649
8.45	8.28	0.17	21600	0.37	0.37	27.18	0.0614	3.086	2.502

Table – 3.45

Al + 30 % RM Load – 10N $\rho = 2.55 \times 10^3$ Kg/m^3

RPM - 300 Vs = 1.885m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.66	7.61	0.05	3600	0.36	0.36	6.786	0.0724	5.447	2.946
7.66	7.60	0.06	7200	0.34	0.34	13.572	0.0423	3.267	1.766
7.66	7.54	0.12	10800	0.36	0.36	20.358	0.0578	4.357	2.356
7.66	7.51	0.15	14400	0.26	0.26	27.144	0.0542	4.084	2.208
7.66	7.48	0.18	18000	0.36	0.36	33.93	0.0346	3.921	2.12
7.66	7.44	0.22	21600	0.37	0.37	40.716	0.0530	3.994	2.159

Table – 3.46

Al + 30 % RM　　　　Load – 10 N　　　　$\rho = 2.55 \times 10^3$ Kg/m^3

RPM = 400　　　　Vs = 3.141 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.80	7.65	0.15	3600	0.36	0.36	11.309	0.130	16.339	5.303
7.80	7.56	0.24	7200	0.34	0.34	22.618	0.1041	13.071	4.242
7.80	7.43	0.37	10800	0.36	0.36	33.927	0.1069	13.435	4.36
7.80	7.27	0.53	14400	0.26	0.26	45.236	0.114	14.433	4.684
7.80	7.18	0.62	18000	0.36	0.36	56.545	0.1075	13.507	4.383
7.80	7.08	0.72	21600	0.37	0.37	67.854	0.1041	13.071	4.242

Table – 3.47

Al + 30 % RM　　　　Load – 20 N　　　　$\rho = 2.55 \times 10^3$ Kg/m^3

RPM = 200　　　　Vs = 1.257 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.99	7.89	0.10	3600	0.38	0.19	4.53	0.216	10.893	4.416
7.99	7.86	0.13	7200	0.50	0.25	9.05	0.141	7.081	2.871
7.99	7.78	0.21	10800	0.50	0.25	13.59	0.1517	7.625	3.102
7.99	7.72	0.27	14400	0.48	0.24	18.12	0.1463	7.352	3.049
7.99	7.68	0.31	18000	0.48	0.24	22.65	0.112	6.753	2.738
7.99	7.61	0.38	21600	0.50	0.25	27.18	0.1373	6.899	2.797

Table – 3.48

Al + 30 % RM   Load – 20 N $\rho = 2. 55 \times 10^3$ Kg/m^3

RPM = 300   Vs 1.885m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	W_r × 10^{-6} (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.42	8.22	0.20	3600	0.48	0.24	6.786	0.2891	21.786	5.89
8.42	7.96	0.46	7200	0.58	0.29	13.572	0.3324	25.05	6.77
8.42	7.66	0.76	10800	0.66	0.33	20.358	0.3662	27.596	7.46
8.42	7.32	1.10	14400	0.48	0.24	27.144	0.3975	29.95	8.098
8.42	7.02	1.40	18000	0.62	0.31	33.93	0.4047	30.56	8.246
8.42	6.80	1.62	21600	0.52	0.26	40.716	0.3903	29.41	7.952

Table – 3.49

Al + 30 % RM   Load – 20 N $\rho = 2.55 \times 10^3$ Kg/m^3

RPM = 400   Vs = 3.141 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	W_r × 10^{-6} (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.88	7.46	0.42	3600	0.80	0.40	11.309	0.3643	45.751	7.423
7.88	7.01	0.87	7200	0.84	0.42	22.618	0.3773	47.385	7.689
7.88	6.45	1.43	10800	0.86	0.43	33.927	0.4135	51.924	8.425
7.88	6.04	1.84	14400	0.82	0.41	45.236	0.3991	50.108	8.130
7.88	5.66	2.22	18000	0.98	0.49	56.545	0.3851	48.366	7.848
7.88	5.26	2.62	21600	0.92	0.46	67.855	0.3788	47.567	7.718

Table – 3.50

Al + 30 % RM   Load –30 N $\rho = 2.\ 55 \times 10^3\ Kg/m^3$

RPM = 200   Vs = 1.257 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.07	7.97	0.10	3600	0.36	0.12	4.53	0.2167	10.893	2.944
8.07	7.91	0.16	7200	0.60	0.20	9.06	0.1734	8.714	2.355
8.07	7.79	0.28	10800	0.72	0.24	13.59	0.2023	10.167	2.748
8.07	7.65	0.42	14400	0.66	0.22	18.12	0.2276	11.437	3.091
8.07	7.55	0.52	18000	0.63	0.21	22.65	0.2254	11.328	3.062
8.07	7.49	0.58	21600	0.48	0.16	27.18	0.2096	10.530	2.846

Table –3.51

Al + 30 % RM   Load – 30 N $\rho = 2.55 \times 10^3\ Kg/m^3$

RPM = 300   Vs =1.885 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.04	7.76	0.28	3600	0.51	0.19	6.786	0.4047	30.501	5.497
8.04	7.62	0.42	7200	0.72	0.24	13.572	0.3035	22.87	4.122
8.04	7.52	0.52	10800	0.78	0.26	20.358	0.2505	18.881	3.403
8.04	7.42	0.62	14400	0.75	0.25	27.114	0.2240	16.884	3.043
8.04	7.37	0.67	18000	0.375	0.25	33.93	0.1937	14.596	2.631
8.04	7.34	0.70	21600	0.72	0.24	40.716	0.1686	12.708	2.290

Table – 3.52

Al + 30 % RM Load – 30N $\rho = 2.55 \times 10^3$ Kg/m^3

RPM = 400 Vs =3.141 m/sec

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.23	7.72	0.51	3600	0.84	0.28	11.309	0.4424	55.55	6.01
8.23	7.28	0.95	7200	0.87	0.29	22.618	0.4120	51.742	5.597
8.23	6.82	1.41	10800	1.05	0.35	33.927	0.4077	51.198	5.538
8.23	6.29	1.94	14400	0.90	0.30	45.236	0.4207	52.832	5.715
8.23	5.85	2.38	18000	0.99	0.33	56.545	0.4129	51.851	5.609
8.23	5.50	2.73	21600	0.93	0.31	67.854	0.3947	49.564	5.361

Fig. 3.5 (a)

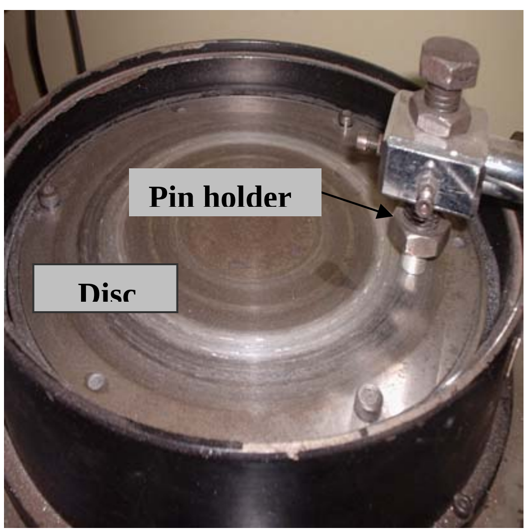


Fig.3.5 (b) Pin on disc

Fig 3.5 (c) Loading panel

Figs. 3.5 (a-c) Experimental set up

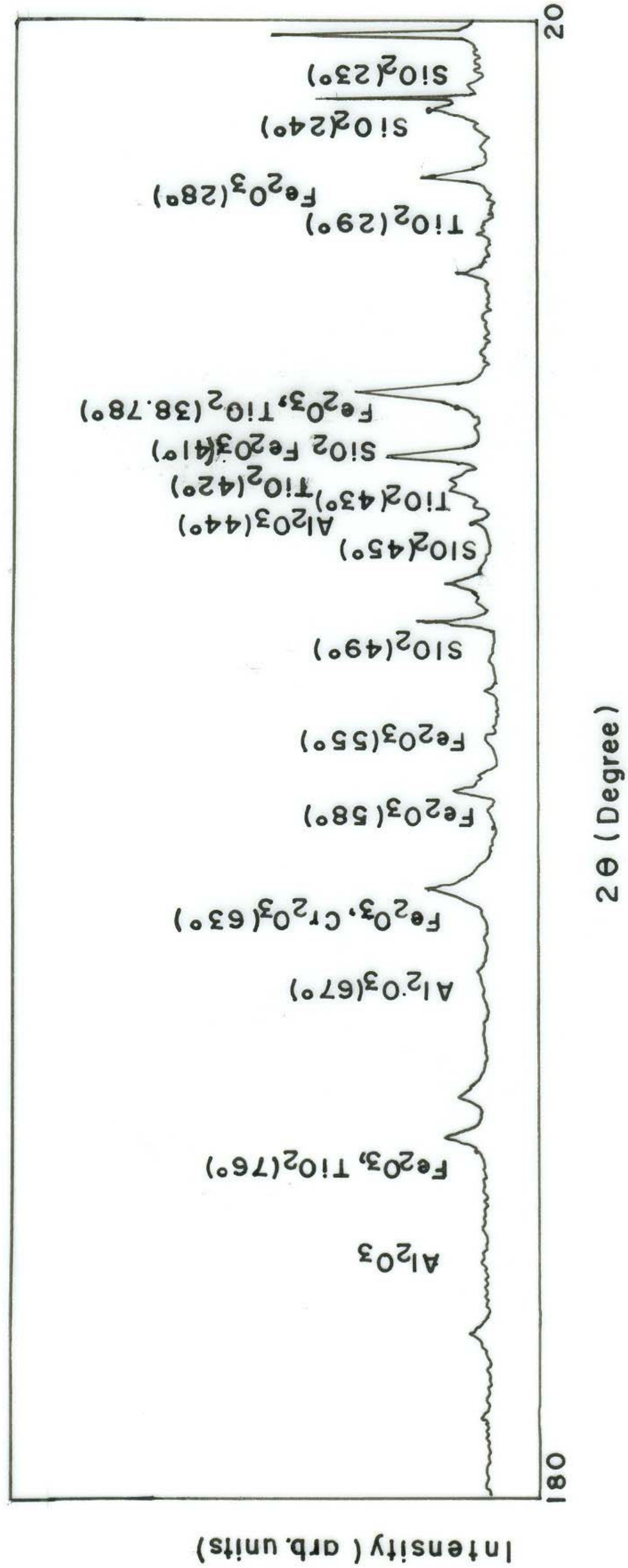


Fig.3.6. XRD Pattern of NALCO red mud

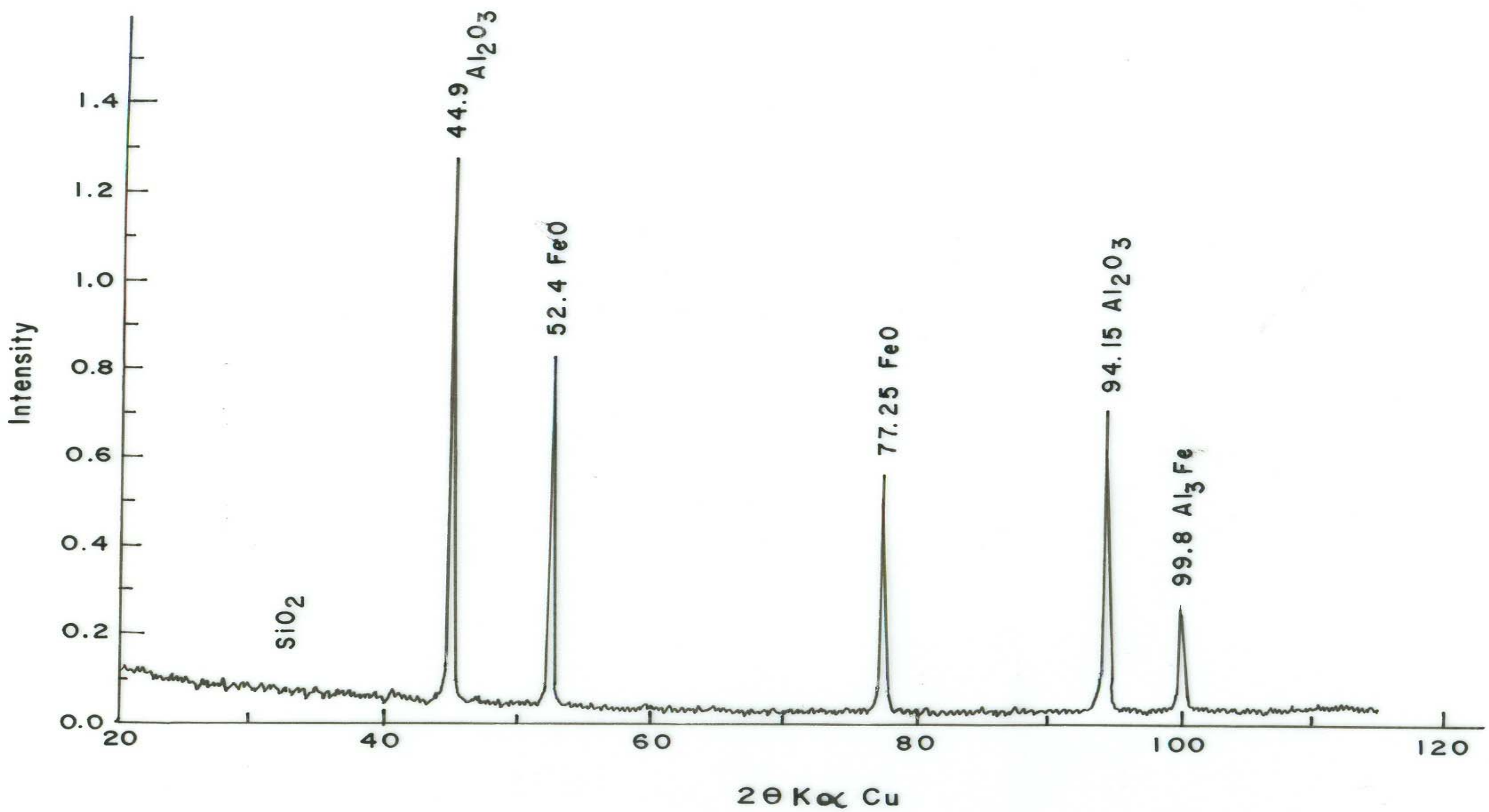


Fig. 3.7 XRD Pattern of 20% red mud composite

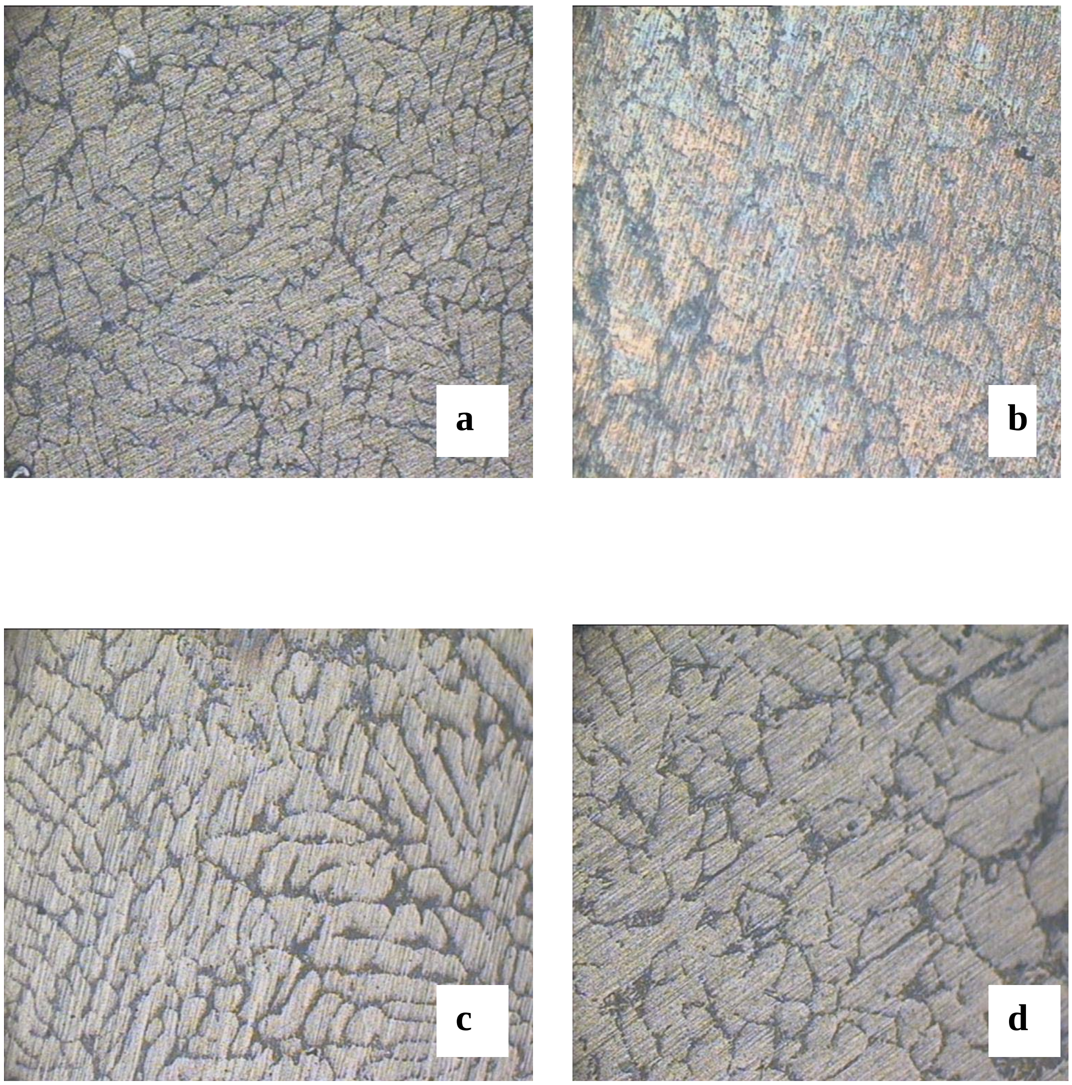


Fig.-3.8 Micrographs showing red mud distribution in the composites of different volume fractions (a) 10% (b) 15% (c) 20% and (d) 30% at (200 X)

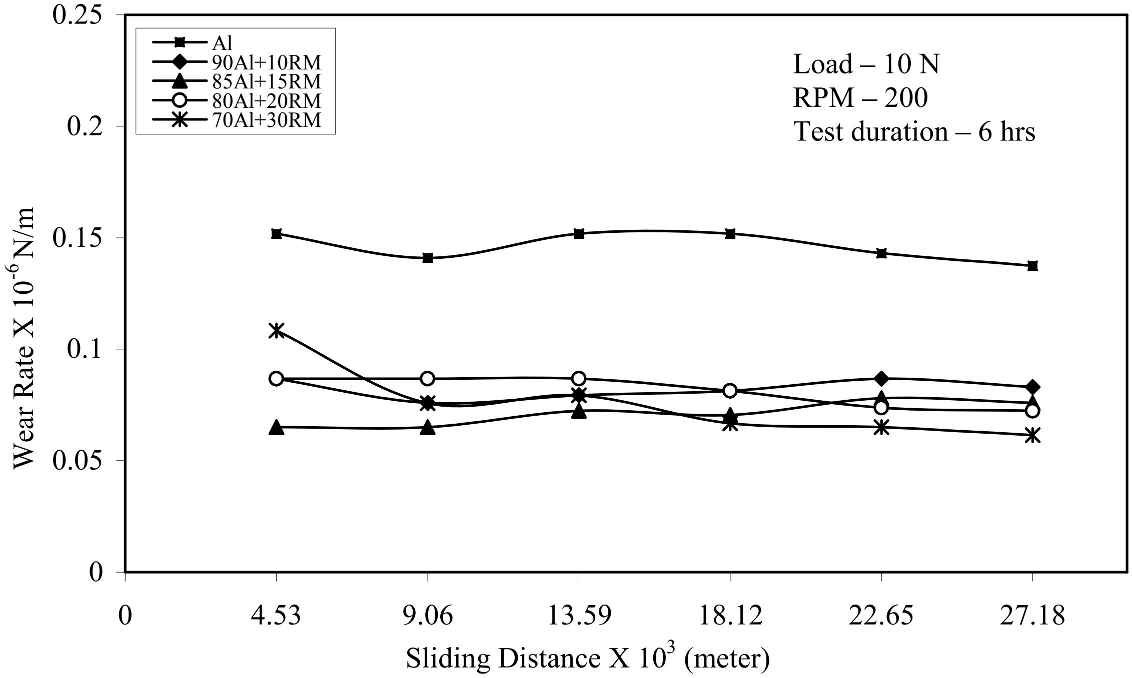


Fig. - 3.9 Variation of wear rate with sliding distance

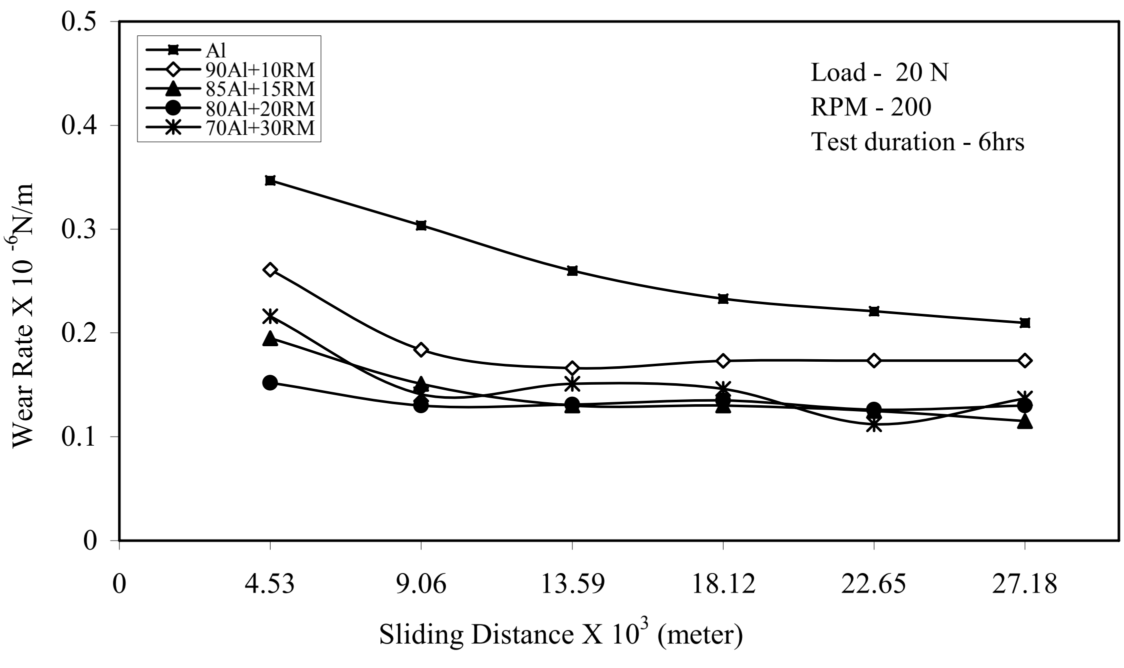


Fig - 3.10 Variation of wear rate with sliding distance

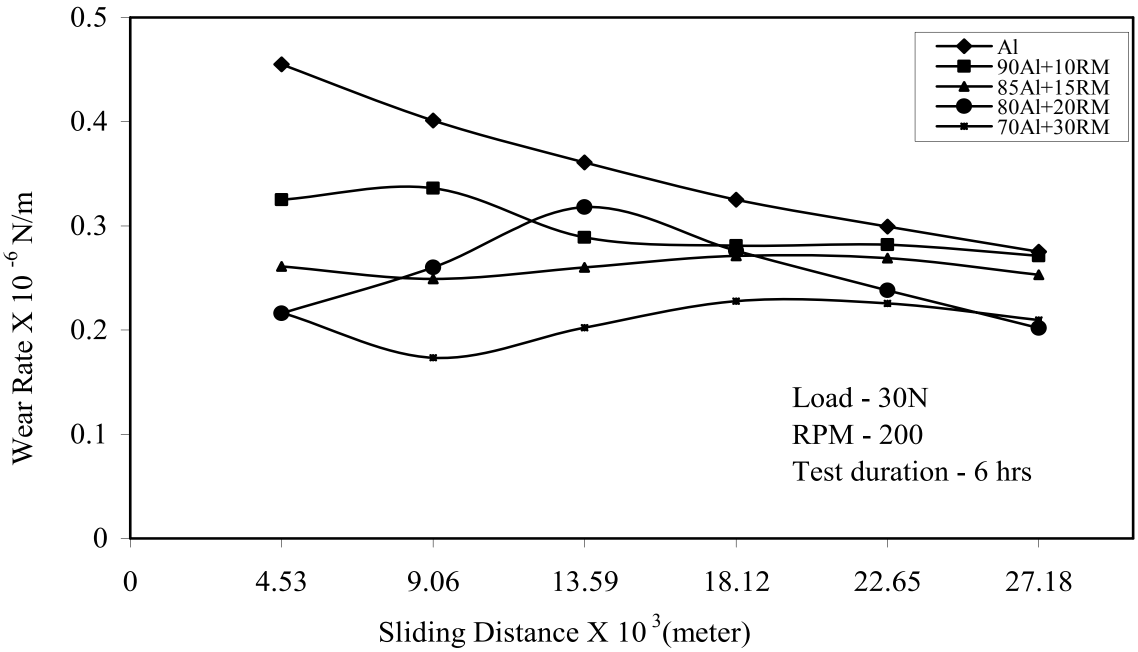


Fig.3.11 Variation of wear rate with sliding distance

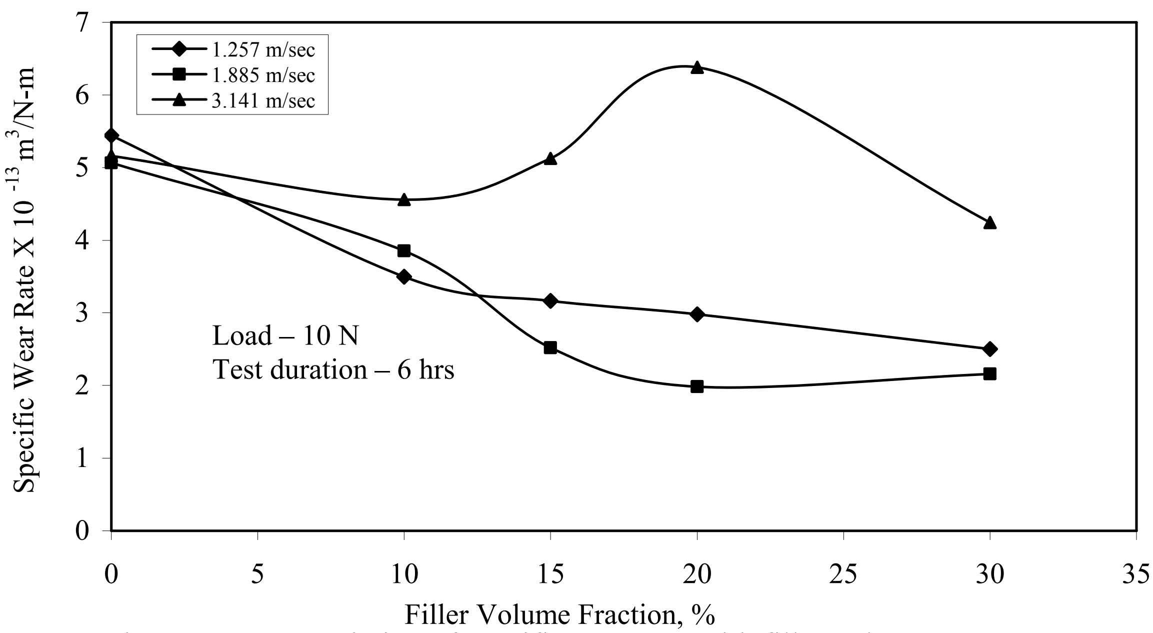


Fig. - 3.12 Variation of specific wear rate with filler volume fraction

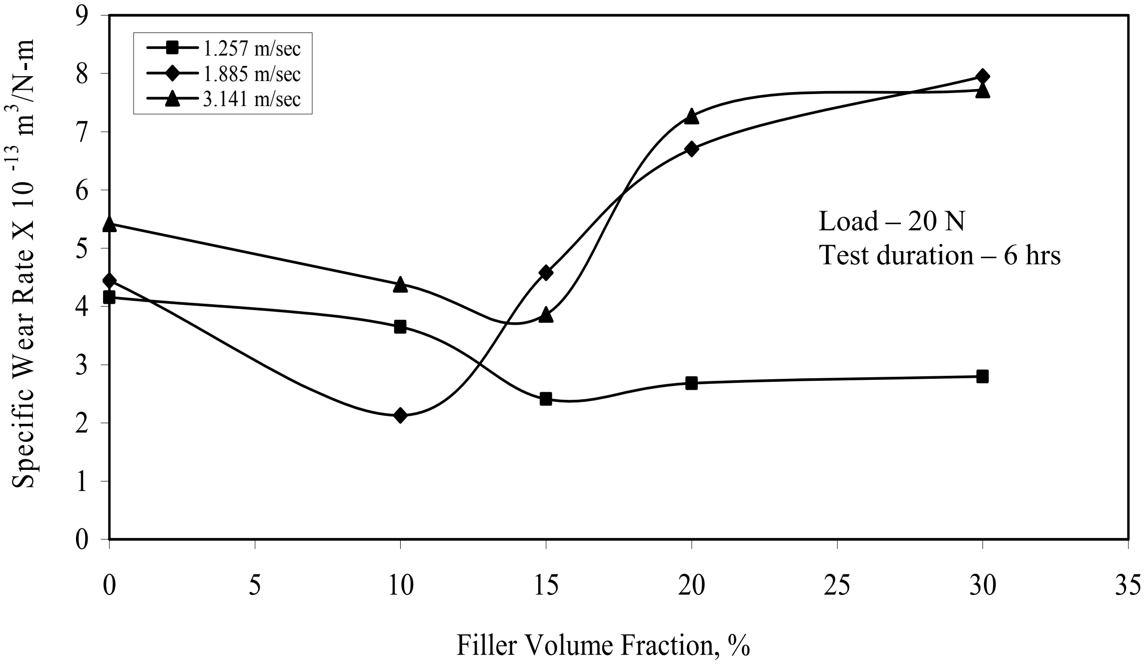


Fig. - 3.13 Variation of specific wear rate with filler volume fraction

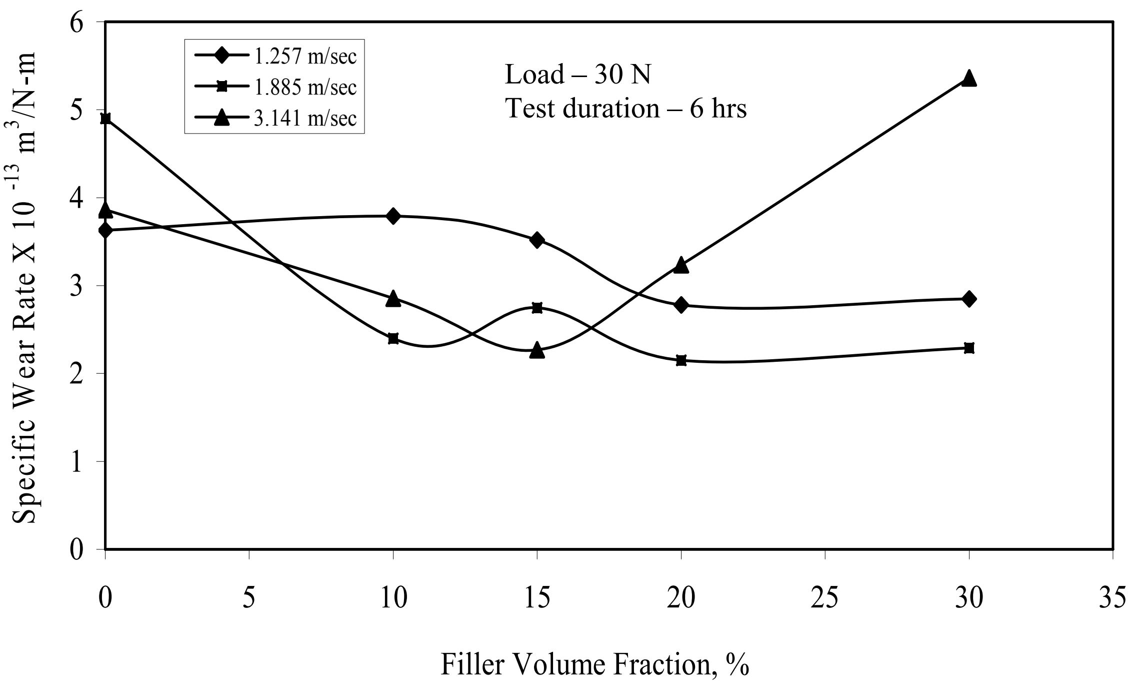


Fig. - 3.14 Variation of specific wear rate with filler volume fraction

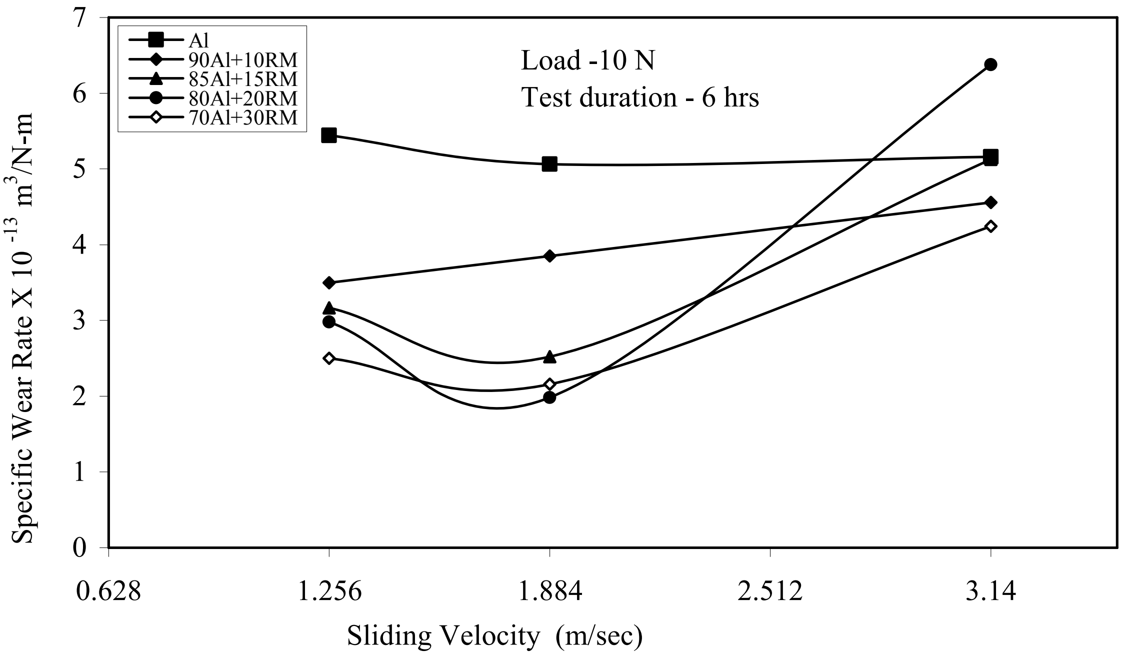


Fig. - 3.15 Variation of specific wear rate with sliding velocity

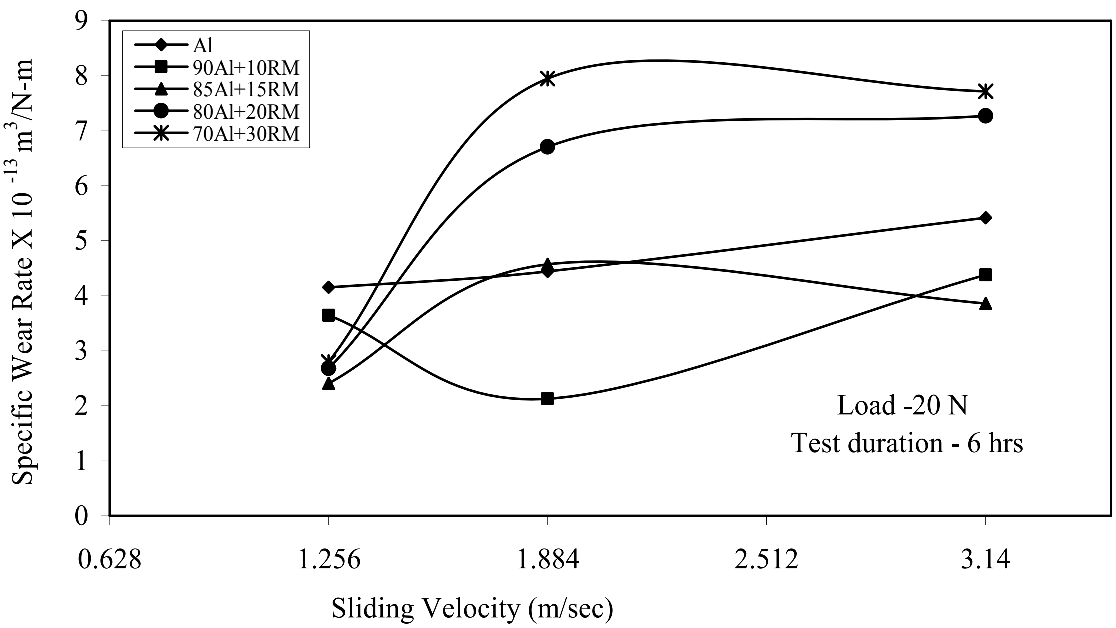


Fig. - 3.16 Variation of specific wear rate with sliding velocity

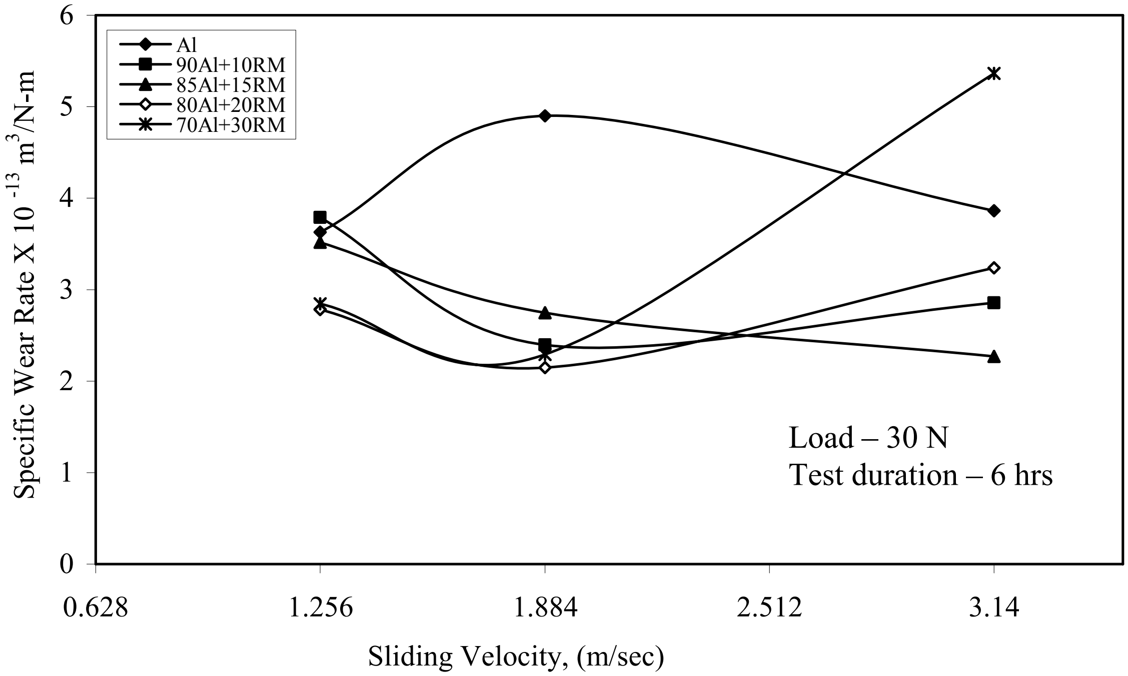


Fig. - 3.17 Variation of specific wear rate with sliding velocity

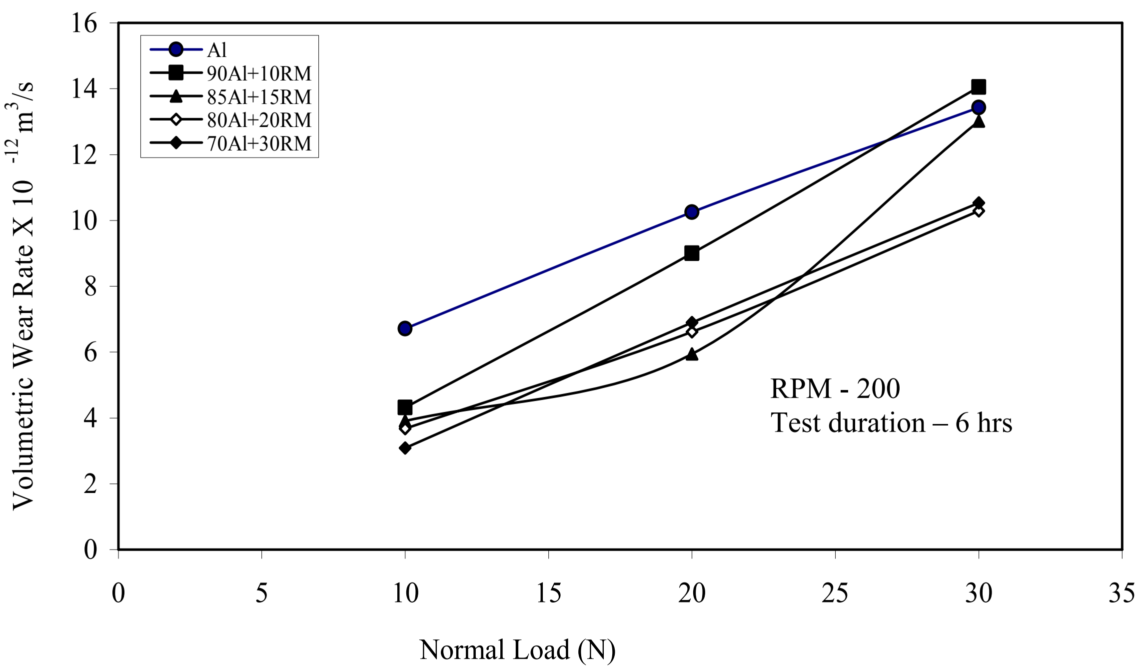


Fig. - 3.18 Variation of volumetric wear rate with normal load

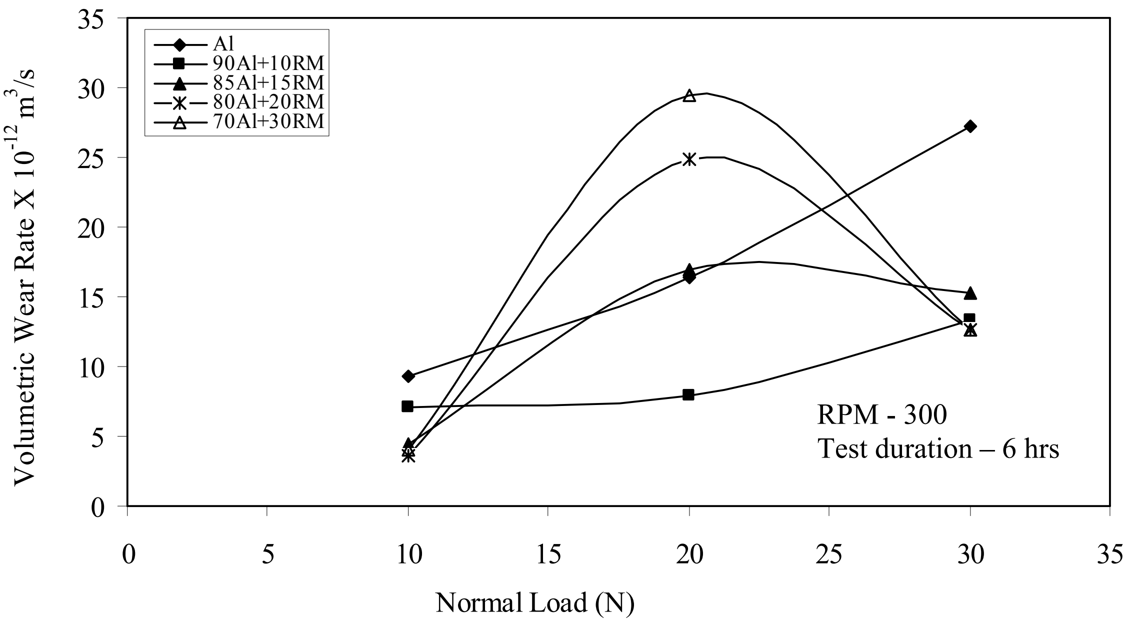


Fig. - 3.19 Variation of volumetric wear rate with normal load

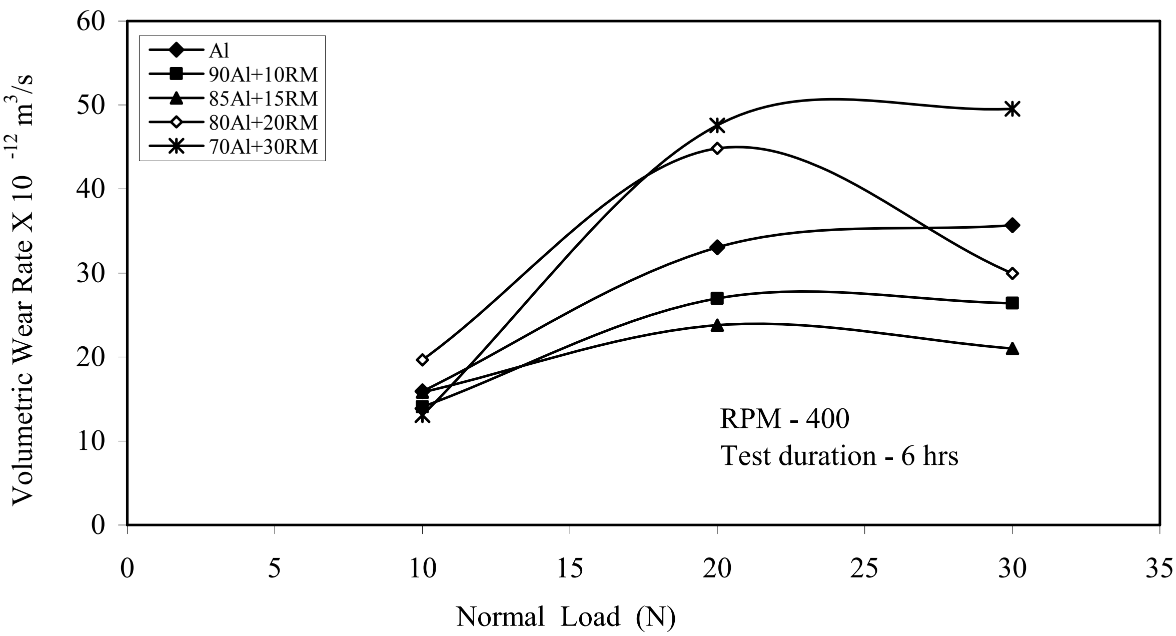


Fig. - 3.20 Variation of volumetric wear rate with normal load

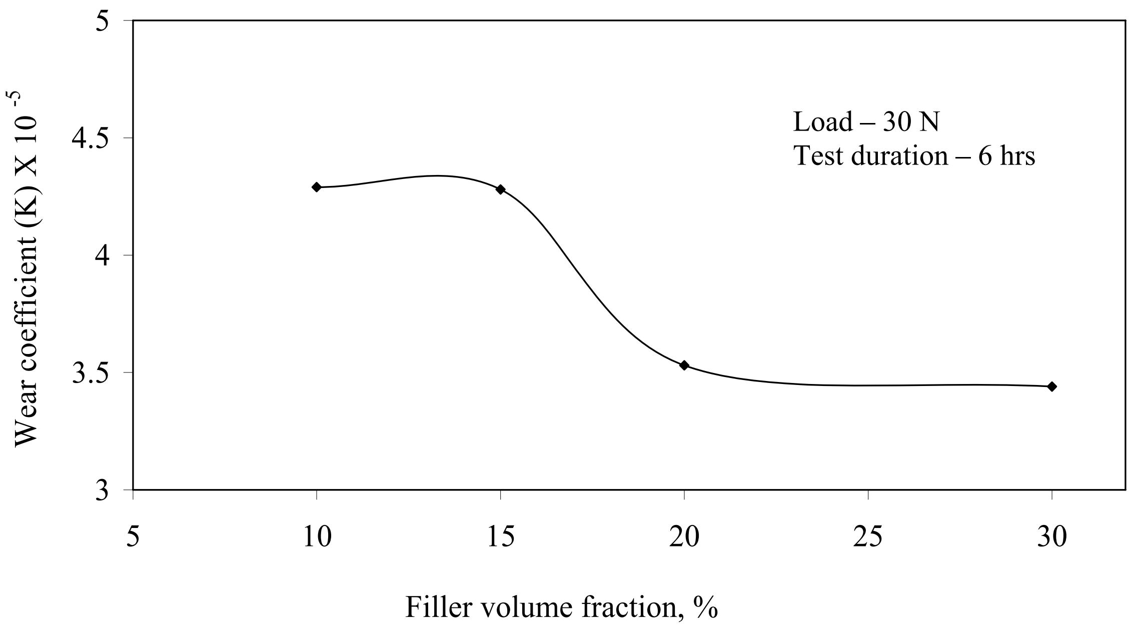


Fig. - 3.21 Variation of wear coefficient with filler volume fraction

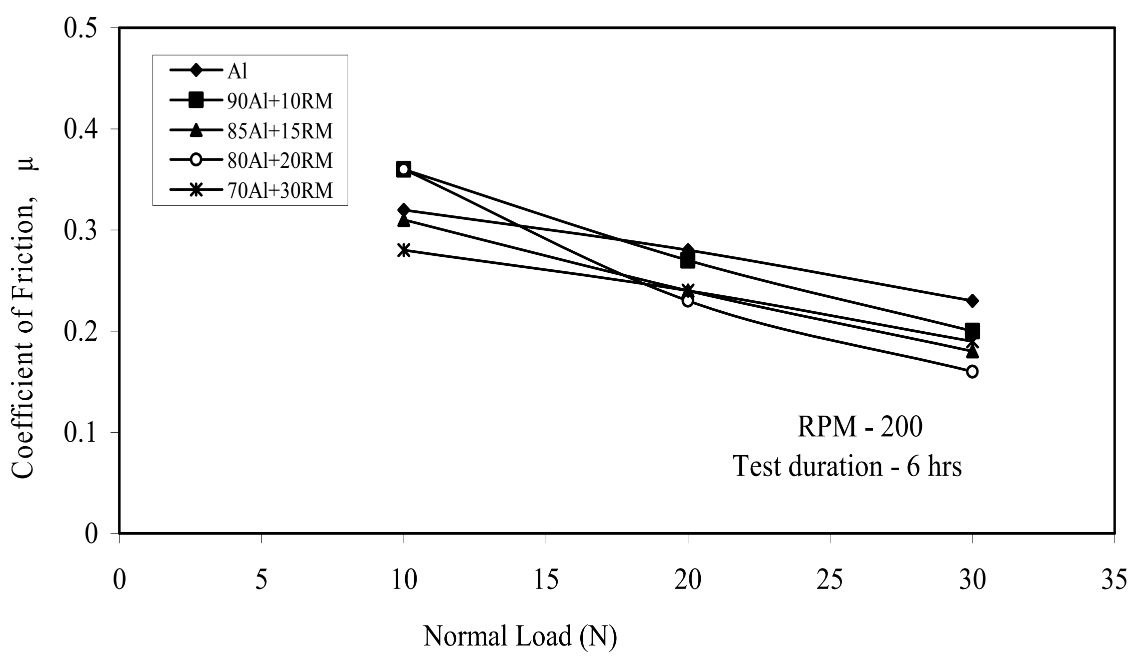


Fig. - 3.22 Variation of coefficient of friction with normal load

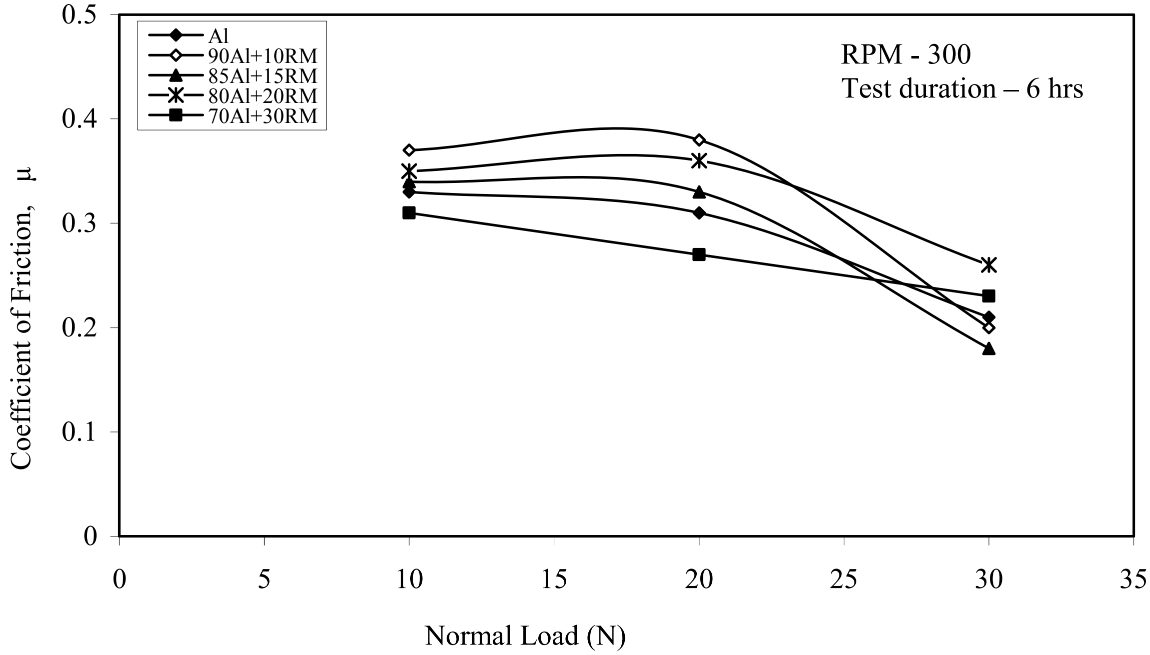


Fig. - 3.23 Variation of coefficient of friction with normal load

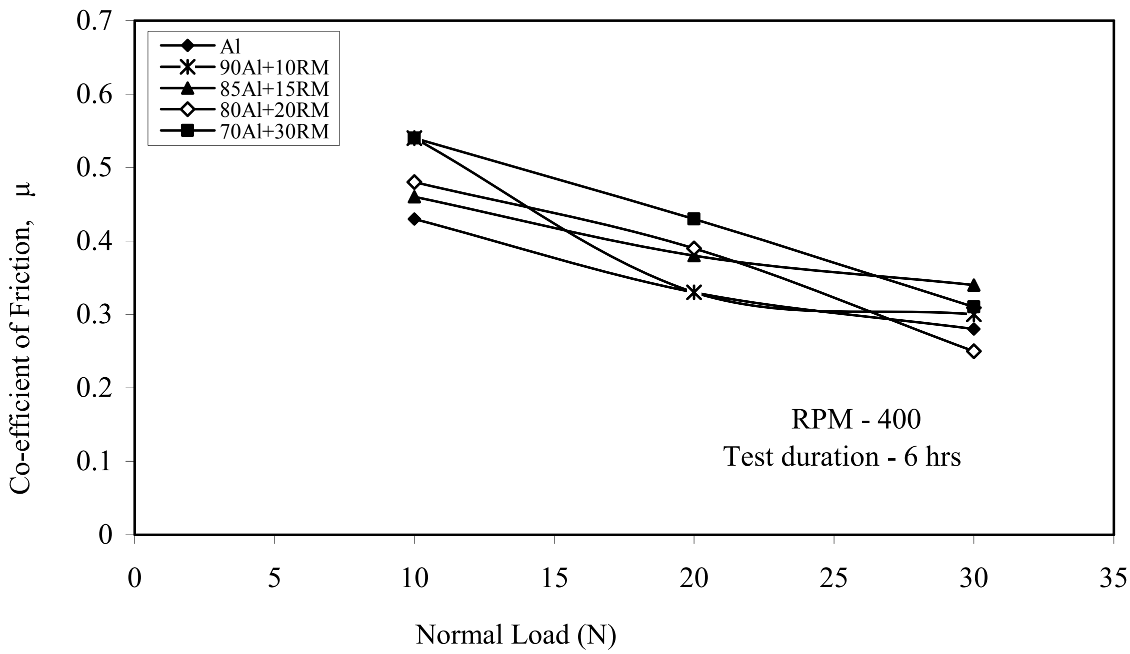
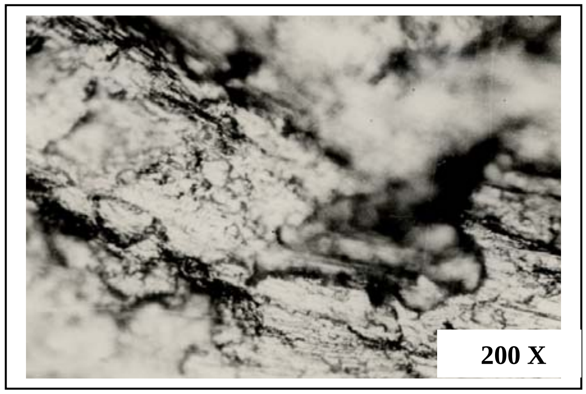
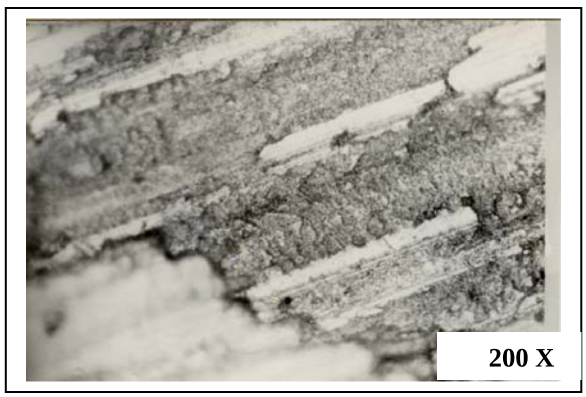


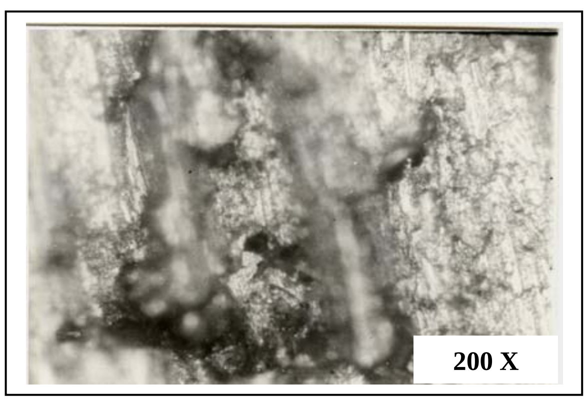
Fig.3.24 Variation of coefficient of friction with normal load



(a)

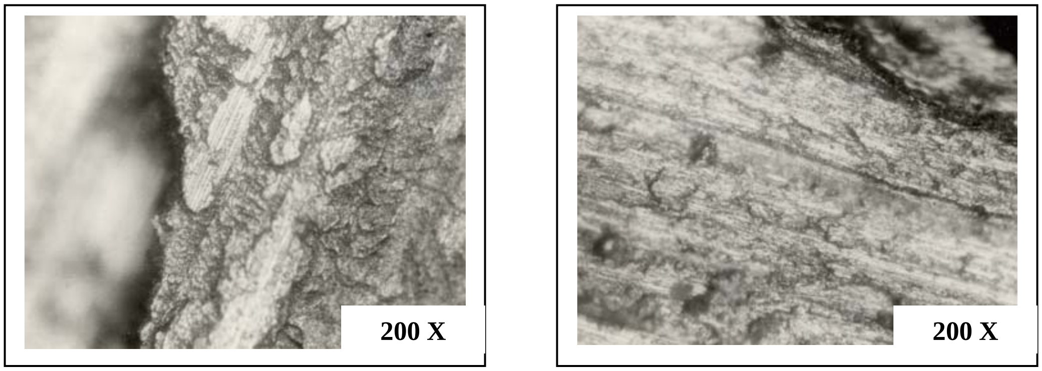


(b)



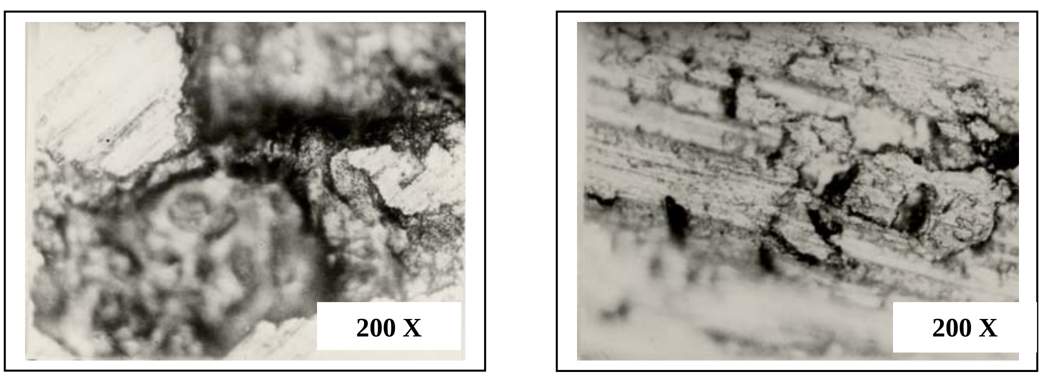
(c)

Figs. 3.25 Micrographs showing wear surface of 10% red mud (a) load 20N & 300 rpm (b) load 20N & 400 rpm & (c) load 30N & 400 rpm.



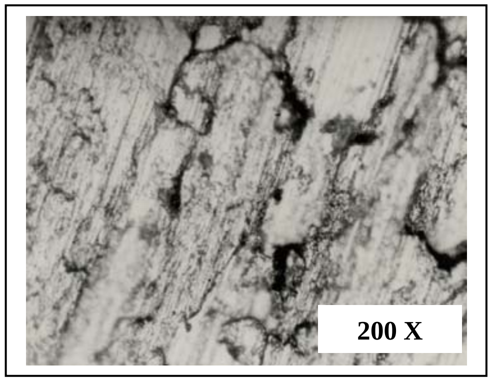
(a) **(b)**

Figs. 3.26 Micrographs showing wear surface of 15% red mud (a) load 20N & 300 rpm (b) load 20N & 400 rpm



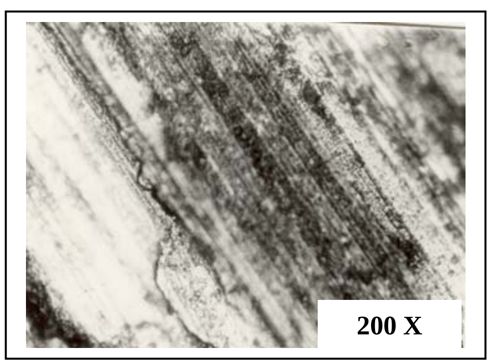
(a) **(b)**

Figs. 3.27 Micrographs showing wear surface of 20% red mud (a) load 10N & 200 rpm (b) load 20N & 200 rpm



(c)

(d)



(e)

Fig. 3.27 Micrographs showing wear surface of 20% red mud (c) load 30N & 200 rpm (d) load 10N & 300 rpm & (e) load 20N & 400 rpm

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CHAPTER – 4

EFFECT OF HEAT TREATMENT ON WEAR BEHAVIOUR OF ALUMINIUM RED MUD COMPOSITES

4.1 INTRODUCTION

It is concluded from the previous chapter that the specific wear rate of the composite decreases with increase in filler volume fraction. The optimum filler volume for the present case lies between 15 to 20 percent. The specific wear rate equation describes the physical nature of the wear rate as a volume loss of material by a given amount of energy input. Often the wear resistance of a material is referred to specific wear rate which is simply the inverse of wear rate. For the present case we have assumed the lower limit of the filler volume i.e. 15 percent as optimal and has been taken in to consideration for further investigation. It is decided to increase the wear resistance of the composite by heat treatment process. The subsequent section will elaborate the experimental work done and the results obtained there from to achieve the objective.

4.2 Experiment

Most of the engineering properties of metals and alloys are related to their structure. Equilibrium structure can be predicted for an alloy with the help of an equilibrium diagram. Mechanical properties can be changed by varying the relative properties of micro constituents. In practice change in mechanical properties are achieved by the process of heat treatment. The process consists of heating a metal or alloy to a specific predetermined temperature, holding at this temperature for required time and finally cooling from this temperature. All these operations are carried out in solid state. Sometimes it becomes necessary to repeat these operations to impart some characteristics. Heat treatment of metals is also an important operation in the final fabrication process of many engineering components. The object of this process is to make the metal better suited, structurally and physically, for some specific applications.

In the present investigation the prepared test samples (15% by weight of red mud) was heated in furnace up to 350^0C, 400^0C, 450^0C and 500^0C and holding at these temperature for one and half hour followed by air (at 35^0C temperature) and water (at 25^0C temperature) quenching for all the heat treatment temperature selected and water (at 15^0C and 5^0C temperature) quenching for only 400^0C and 450^0C. After quenching the samples were tested for prediction of wear behavior.

HEAT TREATMENT

In the present investigation the prepared test samples (15% by volume of red mud) was heated in furnace up to 350^0C, 400^0C, 450^0C and 500^0C and holding at these higher temperature for 1 hr. 30 minutes followed by air cooling (at 35^0C temp) and Water (at 25^0C temp) quenching for all the four heating temperature and water (at 15^0C & 5^0C temp.) quenching for only heating temperature of 400^0C & 450^0C. After quenching the samples are cooled to room temperature for further prediction of wear behaviors.

4.3 HARDNESS TEST

The hardness of the heat treated samples was measured using a Leitz Wetzlar Germant-088303, Vickers micro hardness measuring machine with a load of 0.4903 N. The load was applied for 30 seconds In order to eliminate possible segregation effect a minimum of three hardness readings were taken for each specimen at different locations of the test samples. The values of the hardness number for different test samples were presented in the table 4.1.

4.4 WEAR TEST

The wear tests were performed for heat treated aluminum red mud samples on Pin-On-Disc wear testing machine. A constant sliding velocity of 1.257 m/sec was maintained for the entire test. The experimental procedure remains same as described in chapter–3, art 3.6.4. Results of wear test of different heat treated samples at different test conditions are tabulated and presented in table 4.2 to 4.37.

4. 5 RESULTS AND DISCUSSION

Based on the experiment and tabulated results, various graphs are plotted and presented below for comparison.

Wear rate of the composite with air cooling after different heat treatment temperatures for three loads (10 N, 20 N, and 30 N) are shown in Figs. 4.1 (a-d). It is noted from the plots that the wear rate almost remains same as the sliding distance increases and increases with increase in applied load. However there is much decrease in the value of the wear rate for all loads when compared with untreated samples.

Figs. 4.2 (a-d) Shows the variation of wear rate of the heat treated samples with sliding distance for water quenching (25^0C) at different loads. It is seen from this plot that wear rate almost remains same as the sliding distance increases. However at a temperature of 400 and 450^0C the wear rate remains less in comparison to 350^0C and 500^0C. Further to decrease the wear rates, the temperature of the cooling media water has been changed to 15 and 5^0C keeping the heat treated temperature limited to 400^0C and 450^0C.

Figs. 4.2 (e-f), shows the variation of wear rate of the heat treated samples (400 & 450^0C) with sliding distance for cooling water quenching (15 & 5^0C) at different loads. It is clear from these plots that the wear rate of the composite almost remains same as the sliding distance increases.

Figs. 4.3 (a-b) shows the variation of volumetric wear rate with normal loads for both air cooling and water quenching for different heat treatment temperatures. It is observed from the plots that volumetric wear rate increases with the increase of normal loads for both the cases. However its variation is minimum in case of heat treatment temperature at 450^0C with water at 5^0C quenching temperature.

Figs. 4.4 (a-d) shows the specific wear rate of the heat treated composite at different temperature with sliding distance for air cooling at different loads. It is observed from the plot that the specific wear rate first increases and then almost remains same for the entire test period for all cases.

Figs. 4.5 (a-b), shows the specific wear rate of the composite with different quenching temperature for different loads. It is clear from the plot that at higher loads and low temperature of the quenching media the specific wear rate of the composite decreases. It can be conclude in general from these plots that by choosing suitably the heat treatment temperature and the cooling/quenching media the wear rate of the composite can be controlled.

Figs. 4.6 (a-d), presents the effect of load on coefficient of friction as sliding distance changes both for air and water cooling. It can be seen that the composite at some loads showing increase in the value of coefficient of friction and there is a decrease in the value of coefficient of friction for some other cases. But almost remains constant through out the experiment. This reduction in coefficient of friction occurs likely as a result of particulates standing above the surface. Hence, the contacting surface area of the specimen becomes smaller. In addition this decrease in coefficient of friction may be attributed to the wear of the matrix from the pin surface leaving the particulates standing proud. A similar of coefficients of friction has been observed by M.H. Korkut [197] for their newly developed Al 2024\SiFe and Al 2024\SiFe\Al_2O_3 composites.

Fig. 4.7 (a-b) shows the comparison of wear rate with normal loads with and without heat treatment for all temperatures. It clearly indicates that for all the cases, wear rate increases as the load increases. However the variation of wear rate for without heat treatment is maximum and it is minimum for heat treatment temperature at 450^0C with 5^0C water quenching temperature.

Figs. 4.8 (a-c), shows the comparison of specific wear rate with and without heat treatment for different loads. It is observed from these plots that the samples heat treated and subsequent quenching at a temperature of 15 & 5^0C showed higher wear rate at lower loads. At these temperatures the hardness of the heat treated samples showed lower values which leads to higher wear rate. The lower hardness in these samples is expected due to decrease in bonding / cohesive strength between the particles which in turn leads to higher wear rate. Hence, at lower loads only normal water quenching is sufficient to get the maximum wear resistance of the composite. However for higher loads to increase the wear resistance it is desirable to go for a suitable cooling media lower than the normal water temperature.

4.6 MICRO STRUCTURAL OBSERVATION

Micrographs of the worn surfaces of the composite heat treated and subsequent cooling by air and water have been investigated.

From the investigation it is found that, wear rate i.e. removal of material form the sample is minimum with aluminium 15% red mud composite, than that of the other composition. It is also noted that wear rate is less at lower sliding velocity i.e. at 200 rpm. Hence to investigate the effect of thermal treatment to improve the wear behavior, aluminium 15% red mud composite is selected. Samples are heated at different temperatures for one and half hours followed by air cooling and water quenching. The worn surfaces (of aluminium 15% red mud composite) made with air cooling from 350^0C and 450^0C are shown in Figs. 4.9 (a) and (b) respectively. Comparing these two figures, it is seen that, for the samples treated at 350^0C [Fig. (4.9 (a)] large number of cavity/pores are formed during sliding. Cavities are joined and aligned along the direction of sliding. In the major area of the surface finer grooves are seen. Where as, when the samples are treated at 450^0C, there is great change in surface morphology as observed in Fig. 4.9 (b). The grooves formed during sliding are wider and deeper than that of Fig. 4.9 (a). Some hard particles aligned along the sliding direction, surrounded by cavity are observed. The grooves were probably caused by removal of red mud particles which causes the debris to be formed from the composite on the steel disc.

During wear test debris were formed due to cracking and spalling of the surface of the samples. During severe wear these debris takes of a flake type appearance. Figs.4.10 (a-c) shows the worn surfaces of the aluminium red mud 15% composites heat treated at 450^0C and water quenched. When the applied load is less i.e. at 10 N, deep groves are observed on the worn surface Fig. 4.10 (a). With increasing the applied load i.e. 20 N, although the grooves are finer than the previous case, but large numbers of cavities are observed. Cavities are joined/connected perpendicular to sliding direction. Some finer particles are aligned in the cavity area along the direction of sliding. With further increase in applied load condition, i.e. at 30 N, the appearance of worn surfaces is completely different. Amount of cavities observed are least. Smaller particles are aligned along with the fine grooves in the direction of sliding Fig. 4.10 (c). This appears to be inhibiting the material loss.

From the above observations, this can be said that, during mild wear the formation of oxide films is substantially accelerated by rubbing contact. It has been observed that [198] the quantity of oxide developed during sliding depends on environmental condition and the debris mainly consists of iron oxide (Fe_2O_3). Hence under mild wear condition, steel disc counter face suffered mild scuffing during any sliding and structure of oxide depends on sliding velocity and applied load [199]. The oxide/ metal layer formed as a result of fragmentation of oxide particles, embedded into the metal surface again. This might generate localized stresses on the specimen surface which is responsible for massive deformation of the surface.

So in our observation crack formation, propagation and alignment of hard particles (red mud) are the consequence of the operating mechanisms. When a sample is quenched, although the grain size of aluminium remains smaller but heating at 450^0C has generated grain growth and matrix hardening. So with increased in applied load the debris which are formed might have got pressed on the surface there by reducing the material loss in these samples.

Table – 4.1

Hardness of heat treated composite samples

Heat treated Temperature (^{0}C)	Air Cooling (VHN) (35^{0}C)	Water Quenching at 25^{0}C (VHN)	Water Quenching at 15^{0}C (VHN)	Water Quenching at 5^{0}C (VHN)
350	60.15	63.66	---	---
400	72.91	80.1	28.2	29.8
450	92.21	100.93	26.3	25.8
500	83.31	80.19	---	---

AIR COOLING

Table – 4.2

Al +15% RM — Load – 10 N — $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 — Vs = 1.257 m/sec — Heating Temp. = 350^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.50	7.482	0.018	3600	0.64	0.64	4.53	0.0390	2.008	1.6284
7.50	7.462	0.038	7200	0.69	0.69	9.06	0.0411	2.1196	1.7189
7.50	7.43	0.07	10800	0.67	0.67	13.59	0.0505	2.6030	2.1109
7.50	7.395	0.105	14400	0.60	0.60	18.12	0.0568	2.9284	2.3748
7.50	7.363	0.137	18000	0.68	0.68	22.65	0.0593	3.0567	2.4788
7.50	7.331	0.169	21600	0.49	0.49	27.18	0.0610	3.1422	2.5482

Table – 4.3

Al +15% RM — Load – 20 N — $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 — Vs = 1.257 m/sec — Heating Temp. = 350^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws ×10^{-13} (m^3/N-m)
7.92	7.872	0.048	3600	1.03	0.515	4.53	0.104	5.3548	2.1712
7.92	7.823	0.097	7200	1.03	0.515	9.06	0.105	5.411	2.194
7.92	7.771	0.147	10800	0.84	0.42	13.59	0.108	5.541	2.247
7.92	7.717	0.203	14400	0.85	0.425	18.12	0.111	5.662	2.296
7.92	7.655	0.265	18000	1.27	0.635	22.65	0.115	5.9125	2.397
7.92	7.60	0.320	21600	1.02	0.51	27.18	0.116	5.95	2.413

Table – 4.4

Al +15% RM   Load – 30 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200   Vs = 1.257 m/sec   Heating Temp. = 350^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.73	7.69	0.04	3600	1.99	0.66	4.53	0.0866	4.4623	1.2062
7.73	7.57	0.16	7200	1.64	0.55	9.06	0.1732	8.9246	2.4125
7.73	7.48	0.25	10800	1.92	0.64	13.59	0.1805	9.2964	2.513
7.73	7.39	0.34	14400	1.69	0.56	18.12	0.1841	9.4824	2.5633
7.73	7.289	0.441	18000	1.84	0.61	22.65	0.191	9.8394	2.6598
7.73	7.2	0.53	21600	1.79	0.59	27.18	0.1913	9.8542	2.6638

Table – 4.5

Al +15% RM   Load – 10 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200   Vs = 1.257 m/sec   Heating Temp. = 400^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.03	8.015	0.015	3600	0.79	0.79	4.53	0.0325	1.6734	1.357
8.03	7.985	0.045	7200	0.66	0.66	9.06	0.0487	2.51	2.0355
8.03	7.96	0.07	10800	0.77	0.77	13.59	0.0505	2.603	2.1109
8.03	7.926	0.104	14400	0.81	0.81	18.12	0.0563	2.9005	2.3522
8.03	7.898	0.132	18000	0.85	0.85	22.65	0.0572	2.9451	2.3883
8.03	7.865	0.165	21600	0.80	0.80	27.18	0.0596	3.0678	2.4879

Table – 4.6

Al +15% RM | Load – 20 N | $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 | Vs = 1.257 m/sec | Heating Temp. = 400^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.06	8.021	0.039	3600	1.47	0.73	4.53	0.0845	4.3507	1.7461
8.06	7.975	0.085	7200	1.3	0.65	9.06	0.092	4.7412	1.9224
8.06	7.923	0.137	10800	1.31	0.66	13.59	0.0989	2.0657	2.0657
8.06	7.863	0.197	14400	0.95	0.47	18.12	0.1067	2.2278	2.2278
8.06	7.803	0.257	18000	1.24	0.62	22.65	0.1113	2.325	2.325
8.06	7.751	0.309	21600	1.29	0.65	27.18	0.1115	5.7452	2.3295

Table – 4.7

Al +15% RM | Load – 30 N | $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 | Vs = 1.257 m/sec | Heating Temp. = 400^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.84	7.8	0.04	3600	1.71	0.57	4.53	0.0866	4.4623	1.2062
7.84	7.72	0.12	7200	1.80	0.60	9.06	0.1299	6.6934	1.8094
7.84	7.64	0.2	10800	1.89	0.63	13.59	0.1444	7.4372	2.0104
7.84	7.54	0.3	14400	1.45	0.48	18.12	0.1624	8.3668	2.2617
7.84	7.46	0.68	18000	0.87	0.29	22.65	0.1646	8.4784	2.2919
7.84	7.38	0.46	21600	0.87	0.29	27.18	0.166	8.5527	2.312

Table – 4.8

Al +15% RM Load – 10 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec Heating Temp. = 450^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.05	8.04	0.01	3600	0.73	0.73	4.53	0.0217	1.1156	0.9047
8.05	8.021	0.029	7200	0.60	0.60	9.06	0.0314	1.6176	1.3118
8.05	7.997	0.053	10800	0.61	0.61	13.59	0.0383	1.9708	1.5983
8.05	7.947	0.103	14400	0.69	0.69	18.12	0.0558	2.8726	2.3295
8.05	7.921	0.129	18000	0.7	0.7	22.65	0.0559	2.8782	2.3341
8.05	7.886	0.164	21600	0.59	0.59	27.18	0.0592	3.0492	2.4728

Table – 4.9

Al +15% RM Load – 20 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec Heating Temp. = 450^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.07	8.047	0.023	3600	1.08	0.54	4.53	0.0498	2.5658	1.0404
8.07	8.012	0.058	7200	1.04	0.52	9.06	0.0628	3.2352	1.3118
8.07	7.943	0.127	10800	0.13	0.57	13.59	0.0917	4.7226	1.9149
8.07	7.88	0.19	14400	0.93	0.47	18.12	0.1029	5.299	2.1486
8.07	7.83	0.24	18000	1.01	0.51	22.65	0.1039	5.3548	2.1712
8.07	7.76	0.31	21600	0.78	0.39	27.18	0.1119	5.7638	2.3371

Table – 4.10

Al +15% RM　　Load – 30 N　　$\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200　　Vs = 1.257 m/sec　　Heating Temp. = 450^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.80	7.757	0.043	3600	1.68	0.56	4.53	0.0931	4.797	1.2967
7.80	7.693	0.107	7200	1.46	0.49	9.06	0.1082	5.9683	1.6133
7.80	7.58	0.22	10800	1.70	0.57	13.59	0.1588	8.1809	2.2114
7.80	7.513	0.287	14400	1.34	0.45	18.12	0.1554	8.0042	2.1637
7.80	7.41	0.39	18000	1.30	0.43	22.65	0.1689	8.7015	2.3522
7.80	7.32	0.48	21600	1.35	0.45	27.18	0.1732	8.9246	2.4125

Table – 4.11

Al +15% RM　　Load – 10 N　　$\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200　　Vs = 1.257 m/sec　　Heating Temp. = 500^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.83	7.82	0.01	3600	0.79	0.79	4.53	0.0217	1.1156	0.9047
7.83	7.796	0.034	7200	0.60	0.60	9.06	0.0368	1.8965	1.538
7.83	7.78	0.05	10800	0.75	0.75	13.59	0.0361	1.8593	1.5078
7.83	7.734	0.096	14400	0.76	0.76	18.12	0.052	2.6774	2.1712
7.83	7.70	0.13	18000	0.80	0.80	22.65	0.0563	2.9005	2.3522
7.83	7.664	0.166	21600	0.79	0.79	27.18	0.0599	3.0864	2.5029

Table – 4.12

Al +15% RM　　　Load – 20 N　　　$\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200　　　Vs = 1.257 m/sec　　　Heating Temp. = 500^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.82	7.79	0.03	3600	1.17	0.59	4.53	0.065	3.3467	1.357
7.82	7.74	0.08	7200	0.99	0.49	9.06	0.0866	4.4623	1.8094
7.82	7.69	0.13	10800	0.96	0.48	13.59	0.0938	4.8342	1.9601
7.82	7.63	0.19	14400	0.94	0.47	18.12	0.1029	5.299	2.1486
7.82	7.57	0.25	18000	1.07	0.54	22.65	0.1083	5.5779	2.2617
7.82	7.52	0.30	21600	1.15	0.57	27.18	0.1083	5.5779	2.2617

Table – 4.13

Al +15% RM　　　Load – 30 N　　　$\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200　　　Vs = 1.257 m/sec　　　Heating Temp. = 500^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.92	7.86	0.06	3600	1.59	0.53	4.53	0.1299	6.6934	1.8094
7.92	7.77	0.15	7200	1.17	0.39	9.06	0.1624	8.3668	2.2617
7.92	7.70	0.22	10800	1.54	0.51	13.59	0.1588	8.1809	2.2114
7.92	7.63	0.29	14400	0.99	0.33	18.12	0.1570	8.0879	2.1863
7.92	7.55	0.37	18000	1.26	0.42	22.65	0.1603	8.2552	2.2315
7.92	7.47	0.45	21600	1.32	0.44	27.18	0.1624	8.3668	2.2617

WATER QUENCHING

Table – 4.14

Al +15% RM Load – 10 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec Heating Temp. = 350^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	W_r ×10^{-6} (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.700	7.690	0.010	3600	0.83	0.83	4.53	0.0217	1.1156	0.9047
7.700	7.677	0.023	7200	0.59	0.59	9.06	0.0249	1.2829	1.0404
7.700	7.651	0.049	10800	0.63	0.63	13.59	0.0354	1.8221	1.4776
7.700	7.608	0.092	14400	0.69	0.69	18.12	0.0498	2.5658	2.0808
7.700	7.576	0.124	18000	0.73	0.73	22.65	0.0537	2.7666	2.2436
7.700	7.539	0.161	21600	0.70	0.70	27.18	0.0581	2.9935	2.4276

Table – 4.15

Al +15% RM Load – 20 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec Heating Temp. = 350^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	W_r × 10^{-6} (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.79	7.751	0.039	3600	1.06	0.53	4.53	0.0845	4.3507	1.7641
7.79	7.722	0.068	7200	1.05	0.525	9.06	0.0736	3.7929	1.5380
7.79	7.671	0.119	10800	0.843	0.421	13.59	0.0859	4.4251	1.7943
7.79	7.611	0.179	14400	1.011	0.506	18.12	0.0969	4.9922	2.0242
7.79	7.555	0.235	18000	1.182	0.594	22.65	0.1018	5.2432	2.1260
7.79	7.484	0.306	21600	1.00	0.50	27.18	0.1104	5.6894	2.3069

Table – 4.16

Al +15% RM | Load – 30 N | $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 | Vs = 1.257 m/sec | Heating Temp. = 350^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.66	7.64	0.02	3600	1.56	0.52	4.53	0.0433	2.2311	0.6031
7.66	7.58	0.08	7200	1.57	0.52	9.06	0.0866	4.4623	1.2062
7.66	7.515	0.145	10800	1.44	0.48	13.59	0.1047	5.3919	1.4575
7.66	7.43	0.23	14400	1.74	0.58	18.12	0.1245	6.4145	1.7340
7.66	7.274	0.386	18000	1.56	0.52	22.65	0.1672	8.6122	2.3280
7.66	7.175	0.485	21600	1.53	0.51	27.18	0.1750	9.0176	2.4376

Table – 4.17

Al +15% RM | Load – 10 N | $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 | Vs = 1.257m/sec | Heating Temp. = 400^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.84	7.829	0.011	3600	0.8	0.8	4.53	0.0238	1.2271	0.9951
7.84	7.813	0.027	7200	0.65	0.65	9.06	0.0292	1.5060	1.2213
7.84	7.791	0.049	10800	0.84	0.84	13.59	0.0354	1.8221	1.4776
7.84	7.750	0.090	14400	0.60	0.60	18.12	0.0487	2.5100	2.0355
7.84	7.712	0.128	18000	0.78	0.78	22.65	0.0554	2.8559	2.3160
7.84	7.684	0.156	21600	0.81	0.81	27.18	0.0563	2.9005	2.3522

Table – 4.18

Al +15% RM   Load – 20 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200   Vs = 1.257 m/sec   Heating Temp. = 400^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.50	7.470	0.030	3600	1.28	0.64	4.53	0.0650	3.3467	1.3570
7.50	7.410	0.090	7200	1.10	0.55	9.06	0.0975	5.0201	2.0355
7.50	7.370	0.130	10800	1.08	0.54	13.59	0.0938	4.8342	1.9601
7.50	7.300	0.200	14400	1.06	0.53	18.12	0.1083	5.5779	2.2617
7.50	7.246	0.254	18000	1.20	0.60	22.65	0.1100	5.6671	2.2979
7.50	7.199	0.301	21600	1.12	0.56	27.18	0.1086	5.5965	2.2692

Table – 4.19

Al +15% RM   Load – 30 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200   Vs = 1.257 m/sec   Heating Temp. = 400^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.78	7.721	0.059	3600	1.77	0.59	4.53	0.1278	6.5819	1.7792
7.78	7.656	0.124	7200	1.47	0.49	9.06	0.1343	6.9166	1.8697
7.78	7.580	0.200	10800	1.68	0.56	13.59	0.1444	7.4372	2.0104
7.78	7.500	0.280	14400	1.65	0.55	18.12	0.1516	7.8090	2.1109
7.78	7.430	0.350	18000	1.68	0.56	22.65	0.1516	7.8090	2.1109
7.78	7.351	0.429	21600	1.68	0.56	27.18	0.1548	7.9763	2.1561

Table – 4.20

Al +15% RM Load – 10 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec Heating Temp. = 450^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.21	8.201	0.009	3600	0.94	0.94	4.53	0.0195	1.0040	0.8142
8.21	8.184	0.026	7200	0.86	0.86	9.06	0.0282	1.4502	1.1761
8.21	8.159	0.051	10800	0.92	0.92	13.59	0.0368	1.8965	1.5380
8.21	8.116	0.094	14400	0.95	0.95	18.12	0.0509	2.6216	2.1260
8.21	8.089	0.121	18000	0.77	0.77	22.65	0.0524	2.6997	2.1893
8.21	8.058	0.152	21600	0.59	0.59	27.18	0.0549	2.8261	2.2919

Table – 4.21

Al +15% RM Load – 20 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec Heating Temp. = 450^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv ×10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.09	8.070	0.020	3600	1.16	0.58	4.53	0.0433	2.2311	0.9047
8.09	8.044	0.046	7200	1.12	0.56	9.06	0.0498	2.5658	1.0404
8.09	7.984	0.106	10800	1.08	0.54	13.59	0.0765	3.9417	1.5983
8.09	7.922	0.168	14400	1.14	0.57	18.12	0.0910	4.6854	1.8998
8.09	7.858	0.232	18000	1.08	0.54	22.65	0.1005	5.1763	2.0989
8.09	7.81	0.280	21600	1.24	0.62	27.18	0.1011	5.2060	2.1109

Table – 4.22

Al +15% RM Load – 30 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec Heating Temp. = 450^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.35	8.31	.040	3600	2.01	0.67	4.53	0.0866	4.4623	1.2062
8.35	8.258	0.092	7200	1.89	0.63	9.06	0.0996	5.1316	1.3872
8.35	8.140	0.210	10800	1.56	0.52	13.59	0.1516	7.8090	2.1109
8.35	8.061	0.289	14400	1.68	0.56	18.12	0.1565	8.0600	2.1788
8.35	7.969	0.381	18000	1.65	0.55	22.65	0.1650	8.5007	2.2979
8.35	7.891	0.459	21600	1.65	0.55	27.18	0.1657	8.5341	2.3069

Table – 4.23

Al +15% RM Load – 10 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec Heating Temp. = 500^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.75	7.739	0.011	3600	0.85	0.85	4.53	0.0238	1.2271	0.9951
7.75	7.723	0.027	7200	0.58	0.58	9.06	0.0292	1.5060	1.2213
7.75	7.700	0.050	10800	0.80	0.80	13.59	0.0361	1.8593	1.5078
7.75	7.695	0.091	14400	0.77	0.77	18.12	0.0493	2.5379	2.0581
7.75	7.619	0.131	18000	0.73	0.73	22.65	0.0567	2.9228	2.3703
7.75	7.592	0.158	21600	0.57	0.57	27.18	0.0570	2.9377	2.3823

Table – 4.24

Al +15% RM   Load – 20 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200   Vs = 1.257 m/sec   Heating Temp. = 500^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.92	7.895	0.025	3600	1.36	0.68	4.53	0.0541	2.7889	1.1308
7.92	7.860	0.060	7200	1.16	0.58	9.06	0.0650	3.3467	1.3570
7.92	7.798	0.122	10800	1.14	0.57	13.59	0.0881	4.5367	1.8395
7.92	7.741	0.179	14400	1.28	0.64	18.12	0.0969	4.9922	20242
7.92	7.694	0.226	18000	1.14	0.57	22.65	0.0979	5.0424	2.0446
7.92	7.630	0.290	21600	0.98	0.49	27.18	0.1047	5.3919	2.1863

Table – 4.25

Al +15% RM   Load – 30 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200   Vs = 1.257 m/sec   Heating Temp. = 500^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv ×10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.87	7.810	0.060	3600	1.8	0.60	4.53	0.1299	6.6934	1.8094
7.87	7.725	0.145	7200	1.89	0.63	9.06	0.1570	8.0879	2.1863
7.87	7.645	0.225	10800	1.45	0.48	13.59	0.1624	8.3668	2.2617
7.87	7.560	0.310	14400	1.59	0.53	18.12	0.1678	8.6457	2.3371
7.87	7.481	0.389	18000	1.62	0.54	22.65	0.1685	8.6792	2.3461
7.87	7.395	0.475	21600	1.63	0.54	27.18	0.1714	8.8316	2.3873

Table – 4.26

Al + 15%RM Load – 10 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec

Heating Temp. = 400^{0}C Cooling Water Temp. = 15^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.91	7.85	0.06	3600	0.73	0.73	4.53	0.13007	6.69344	5.428
7.91	7.79	0.12	7200	0.73	0.73	9.06	0.13007	6.69344	5.428
7.91	7.75	0.16	10800	0.74	0.74	13.59	0.11562	5.9497	4.8249
7.91	7.71	0.20	14400	0.84	0.84	18.12	0.10839	5.57786	4.5234
7.91	7.67	0.24	18000	0.68	0.68	22.65	0.10406	5.35475	4.34245
7.91	7.63	0.28	21600	0.77	0.77	27.18	0.10117	5.206	4.22182

Table – 4.27

Al + 15%RM Load – 20 N $\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec

Heating Temp. = 400^{0}C Cooling Water Temp. = 15^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv ×10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
8.08	8.03	0.05	3600	1.08	0.54	4.53	0.10839	5.57786	2.26169
8.08	7.96	0.12	7200	0.95	0.475	9.06	0.13007	6.69344	2.71403
8.08	7.90	0.18	10800	1.21	0.605	13.59	0.13007	6.69344	2.71403
8.08	7.83	0.25	14400	1.34	0.67	18.12	0.13549	6.97233	2.82712
8.08	7.76	0.32	18000	1.25	0.625	22.65	0.13874	7.13967	2.895
8.08	7.71	0.37	21600	1.18	0.59	27.18	0.13368	6.87937	2.78942

Table – 4.28

Al + 15%RM　　Load – 30 N　　$\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200　　Vs = 1.257 m/sec

Heating Temp. = 400^{0}C　　Cooling Water Temp. = 15^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
8.39	8.33	0.06	3600	1.6	0.533	4.53	0.13007	6.693	1.809
8.39	8.28	0.11	7200	1.58	0.527	9.06	0.11923	6.136	1.659
8.39	8.21	0.18	10800	1.8	0.6	13.59	0.13007	6.693	1.809
8.39	8.12	0.27	14400	1.7	0.567	18.12	0.1463	7.53	2.035
8.39	8.04	0.35	18000	1.7	0.567	22.65	0.15175	7.809	2.111
8.39	7.96	0.43	21600	1.64	0.547	27.18	0.15536	7.995	2.161

Table – 4.29

Al + 15%RM　　Load – 10 N　　$\rho = 2.49 \times 10^3$ Kg/m^3

RPM = 200　　Vs = 1.257 m/sec

Heating Temp. = 450^{0}C　　Cooling Water Temp. = 15^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.58	7.74	0.04	3600	0.72	0.72	4.53	0.0867	4.4623	3.6187
7.58	7.48	0.10	7200	0.63	0.63	9.06	0.108	5.5779	4.5234
7.58	7.44	0.14	10800	0.64	0.64	13.59	0.1012	5.206	4.222
7.58	7.39	0.19	14400	0.63	0.63	18.12	0.103	5.299	4.297
7.58	7.35	0.23	18000	0.59	0.59	22.65	0.0997	5.1316	4.1617
7.58	7.31	0.27	21600	0.65	0.65	27.18	0.0976	5.02	4.071

Table – 4.30

Al + 15%RM   Load – 20 N $\rho = 2.49x\ 10^3\ Kg/m^3$

RPM = 200   Vs = 1.257 m/sec

Heating Temp. = 450^0C Cooling Water Temp. = 15^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.84	7.77	0.07	3600	0.86	0.43	4.53	0.1518	7.809	3.166
7.84	7.71	0.13	7200	1.00	0.50	9.06	0.1409	7.251	2.94
7.84	7.64	0.20	10800	0.99	0.495	13.59	0.14453	7.4372	3.01561
7.84	7.58	0.26	14400	0.97	0.485	18.12	0.1409	7.25123	2.9402
7.84	7.53	0.31	18000	0.97	0.485	22.65	0.1344	6.91655	2.8045
7.84	7.48	0.36	21600	1.02	0.51	27.18	0.13007	6.69344	2.71403

Table – 4.31

Al + 15%RM   Load – 30 N $\rho = 2.49\ x\ 10^3\ Kg/m^3$

RPM = 200   Vs = 1.257 m/sec

Heating Temp. = 450^0C Cooling Water Temp. = 15^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.58	7.51	0.07	3600	1.47	0.49	4.53	0.1518	7.809	2.111
7.58	7.45	0.13	7200	1.58	0.527	9.06	0.1409	7.251	1.96
7.58	7.37	0.21	10800	1.51	0.503	13.59	0.15175	7.80901	2.1109
7.58	7.29	0.29	14400	1.4	0.467	18.12	0.15717	8.0879	2.1863
7.58	7.20	0.38	18000	1.61	0.537	22.65	0.16475	8.47836	2.29185
7.58	7.13	0.45	21600	1.64	0.547	27.18	0.16259	8.3668	2.26169

Table – 4.32

Al + 15%RM Load – 10 N $\rho = 2.49x\ 10^3\ Kg/m^3$

RPM = 200 Vs = 1.257 m/sec

Heating Temp. = 400^0C Cooling Water Temp. = 5^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D × 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws $\times 10^{-13}$ (m^3/N-m)
7.79	7.75	0.04	3600	0.86	0.86	4.53	0.08671	4.46229	3.6187
7.79	7.70	0.09	7200	0.88	0.88	9.06	0.09755	5.02008	4.07105
7.79	7.64	0.15	10800	0.85	0.85	13.59	0.10839	5.57787	4.52339
7.79	7.59	0.20	14400	0.87	0.87	18.12	0.10839	5.57787	4.52339
7.79	7.55	0.24	18000	0.77	0.77	22.65	0.10406	5.35475	4.34245
7.79	7.50	0.29	21600	0.79	0.79	27.18	0.10478	5.39194	4.37261

Table – 4.33

Al + 15%RM Load – 20 N $\rho = 2.49x\ 10^3\ Kg/m^3$

RPM = 200 Vs = 1.257 m/sec

Heating Temp. = 400^0C Cooling Water Temp. = 5^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D× 10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv $\times 10^{-12}$ (m^3/sec)	Ws× 10^{-13} (m^3/N-m)
8.10	8.07	0.03	3600	1.18	0.59	4.53	0.06504	3.34672	1.35702
8.10	8.02	0.08	7200	1.44	0.72	9.06	0.08671	4.46229	1.80935
8.10	7.97	0.13	10800	1.41	0.705	13.59	0.09394	4.83415	1.96013
8.10	7.92	0.18	14400	1.25	0.625	18.12	0.09755	5.02008	2.03552
8.10	7.86	0.24	18000	1.18	0.59	22.65	0.10406	5.35475	2.17123
8.10	7.82	0.28	21600	1.10	0.55	27.18	0.10117	5.20601	2.11091

Table – 4.34

Al + 15%RM Load – 30 N $\rho = 2.49\text{x } 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec

Heating Temp. = 400^{0}C Cooling Water Temp. = 5^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D ×10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.73	7.67	0.06	3600	1.9	0.633	4.53	0.13007	6.69344	1.80936
7.73	7.61	0.12	7200	1.8	0.60	9.06	0.13007	6.69344	1.80936
7.73	7.53	0.20	10800	1.8	0.60	13.59	0.14452	7.43716	2.0104
7.73	7.47	0.26	14400	1.9	0.633	18.12	0.14091	7.25123	1.96014
7.73	7.40	0.33	18000	1.86	0.62	22.65	0.14308	7.36278	1.99029
7.73	6.33	0.40	21600	1.88	0.627	27.18	0.14452	7.4372	2.0104

Table – 4.35

Al + 15%RM Load – 10 N $\rho = 2.49\text{x } 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec

Heating Temp. = 450^{0}C Cooling Water Temp. = 5^{0}C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D ×10^3 (m)	$W_r \times 10^{-6}$ (N/m)	Wv × 10^{-12} (m^3/sec)	Ws × 10^{-13} (m^3/N-m)
7.15	7.12	0.03	3600	0.77	0.77	4.53	0.06504	3.3467	2.714
7.15	7.08	0.07	7200	0.66	0.66	9.06	0.07588	3.905	3.1668
7.15	7.04	0.11	10800	0.69	0.69	13.59	0.07949	4.0904	3.3171
7.15	7.00	0.15	14400	0.67	0.67	18.12	0.0813	4.1834	3.3925
7.15	6.96	0.19	18000	0.78	0.78	22.65	0.08238	4.2392	3.4378
7.15	6.92	0.23	21600	0.66	0.66	27.18	0.0831	4.2764	3.468

Table – 4.36

Al + 15%RM Load – 20 N $\rho = 2.49 \text{x } 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec

Heating Temp. = 450^0C Cooling Water Temp. = 5^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	$Wv \times 10^{-12}$	$Ws \times 10^{-13}$ (m^3/N-m)
7.40	7.38	0.02	3600	1.14	0.57	4.53	0.04336	2.2311	0.9047
7.40	7.34	0.06	7200	1.19	0.595	9.06	0.06504	3.3467	1.357
7.40	7.30	0.10	10800	1.24	0.62	13.59	0.07226	3.7186	1.5078
7.40	7.26	0.14	14400	1.28	0.64	18.12	0.07588	3.9045	1.5832
7.40	7.20	0.20	18000	1.25	0.625	22.65	0.08671	4.4623	1.8094
7.40	7.15	0.25	21600	1.15	0.575	27.18	0.09033	4.6482	1.8847

Table – 4.37

Al + 15%RM Load – 30 N $\rho = 2.49 \text{x } 10^3$ Kg/m^3

RPM = 200 Vs = 1.257 m/sec

Heating Temp. = 450^0C Cooling Water Temp. = 5^0C

m_1 (gm)	m_2 (gm)	Δm (gm)	t (sec)	F_f (kg^f)	μ	R.D $\times 10^3$ (m)	$W_r \times 10^{-6}$ (N/m)	$Wv \times 10^{-12}$ (m^3/sec)	$Ws \times 10^{-13}$ (m^3/N-m)
7.93	7.89	0.04	3600	1.5	0.5	4.53	0.08671	4.4623	1.2062
7.93	7.84	0.09	7200	1.9	0.633	9.06	0.09755	5.0201	1.357
7.93	7.78	0.15	10800	2.0	0.667	13.59	0.1084	5.5779	1.5078
7.93	7.72	0.21	14400	1.9	0.633	18.12	0.11381	5.85676	1.5832
7.93	7.65	0.28	18000	1.8	0.6	22.65	0.1214	6.2472	1.6887
7.93	7.59	0.34	21600	1.5	0.5	27.18	0.12285	6.32158	1.70883

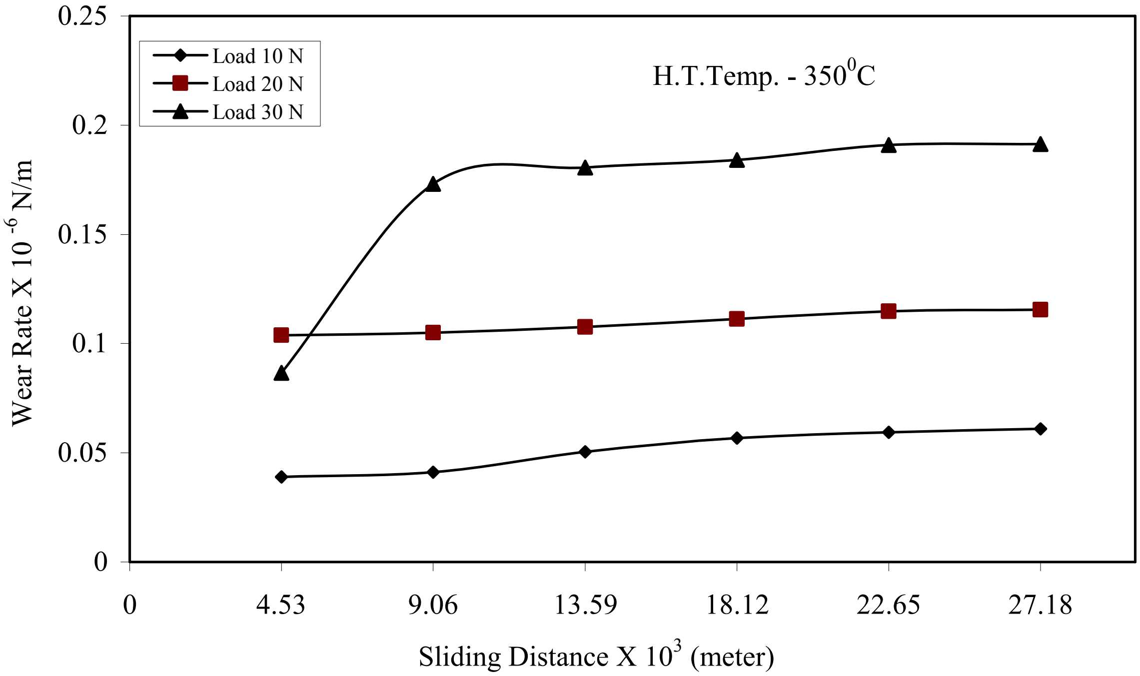


Fig. 4.1 (a)

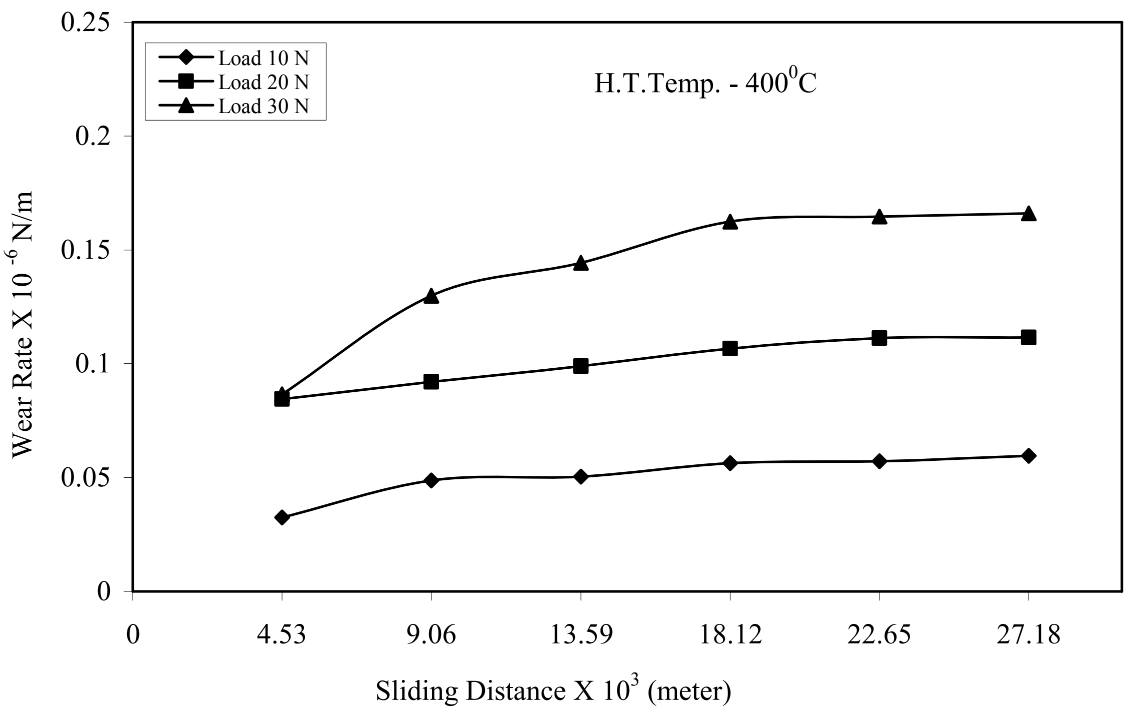


Fig. 4.1 (b)

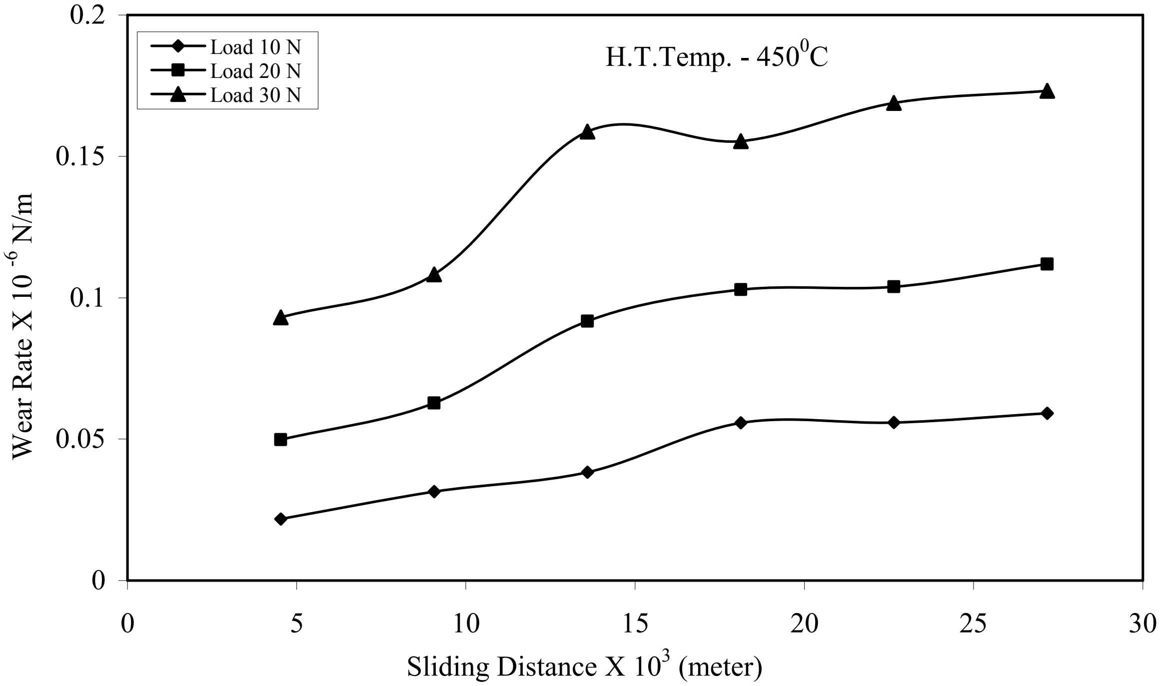


Fig. 4.1 (c)

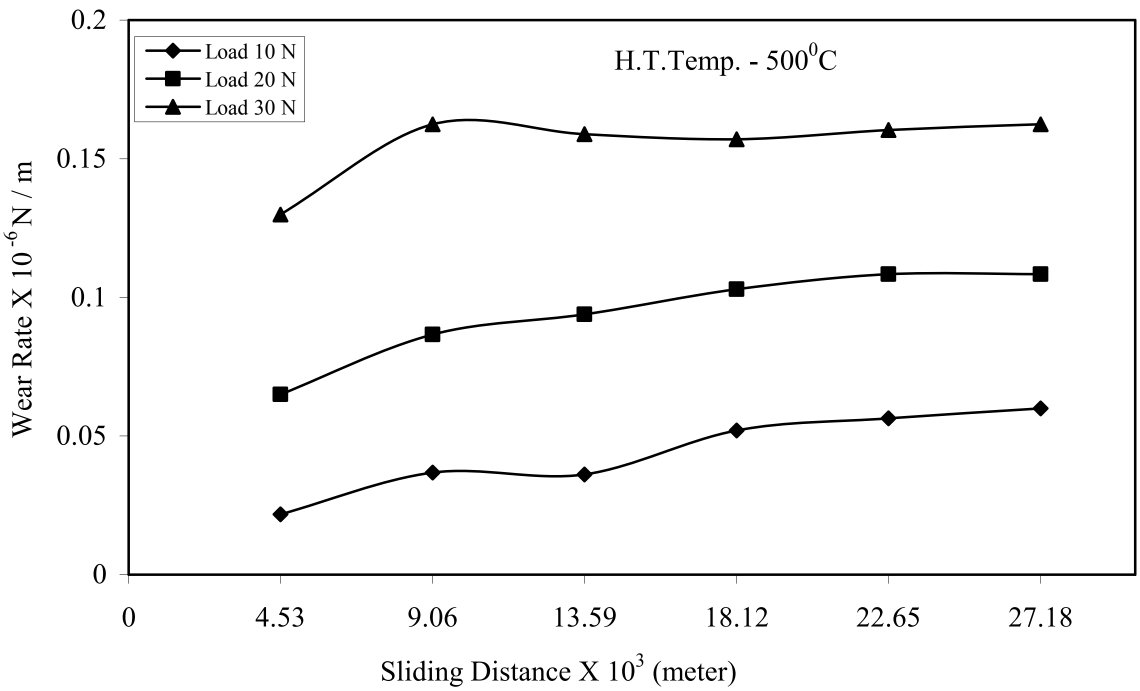


Fig. 4.1 (d)

Figs. 4.1 (a-d) Variation of wear rate with sliding distance for air cooling.

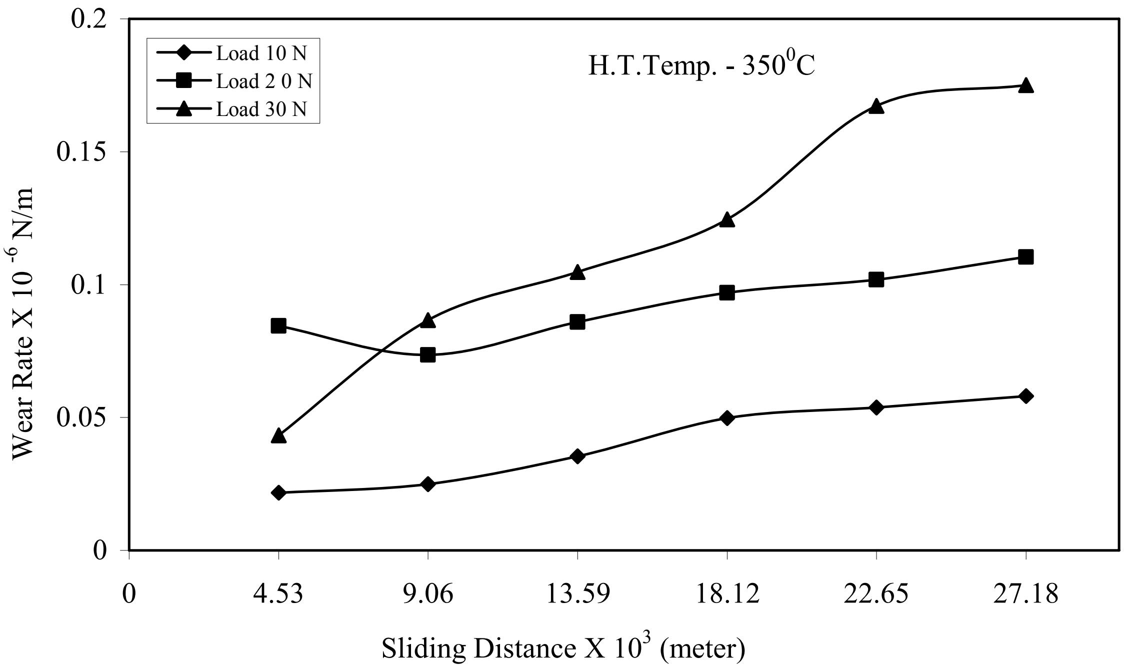


Fig. 4.2 (a)

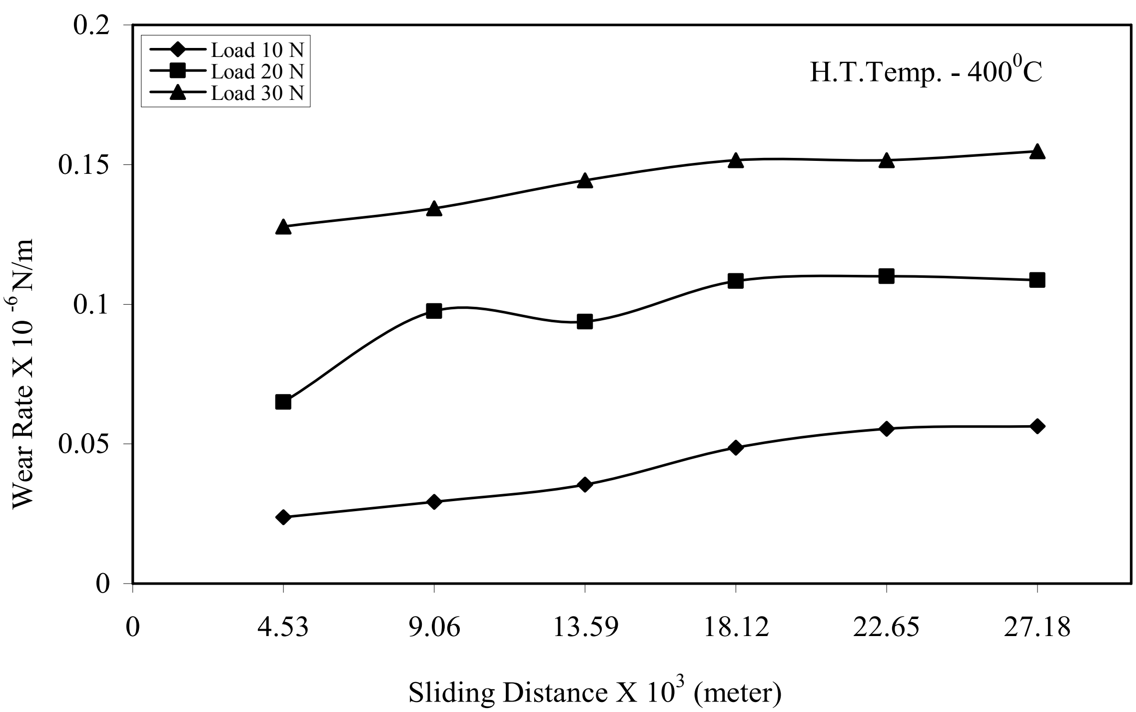


Fig. 4.2 (b)

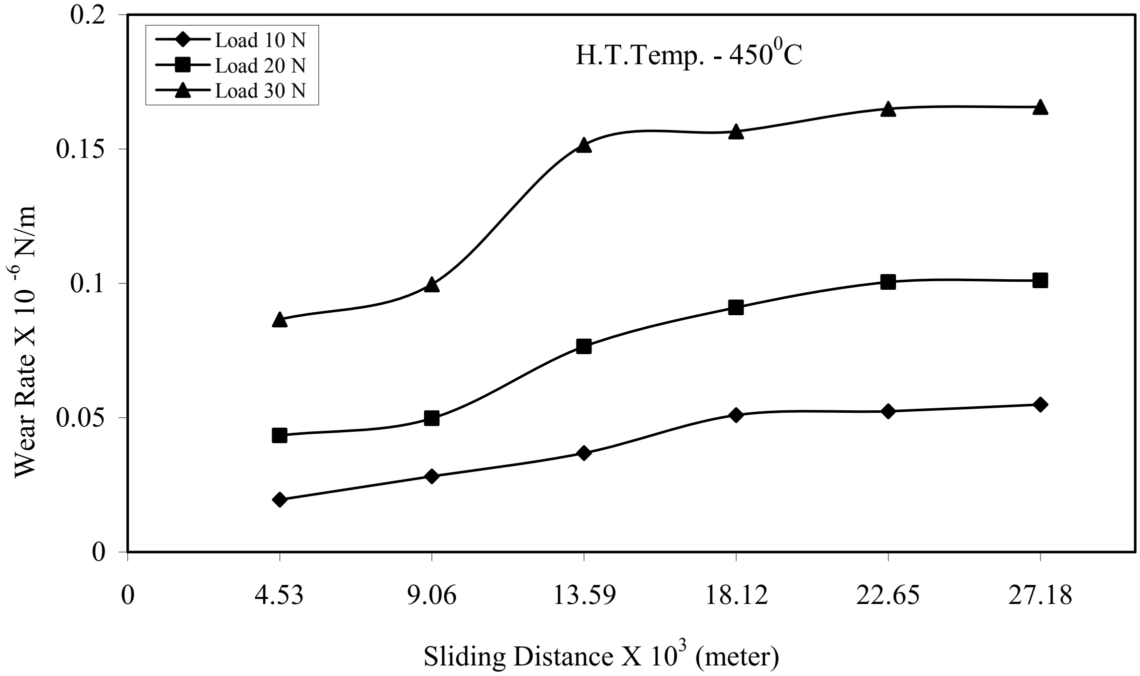


Fig. 4.2 (c)

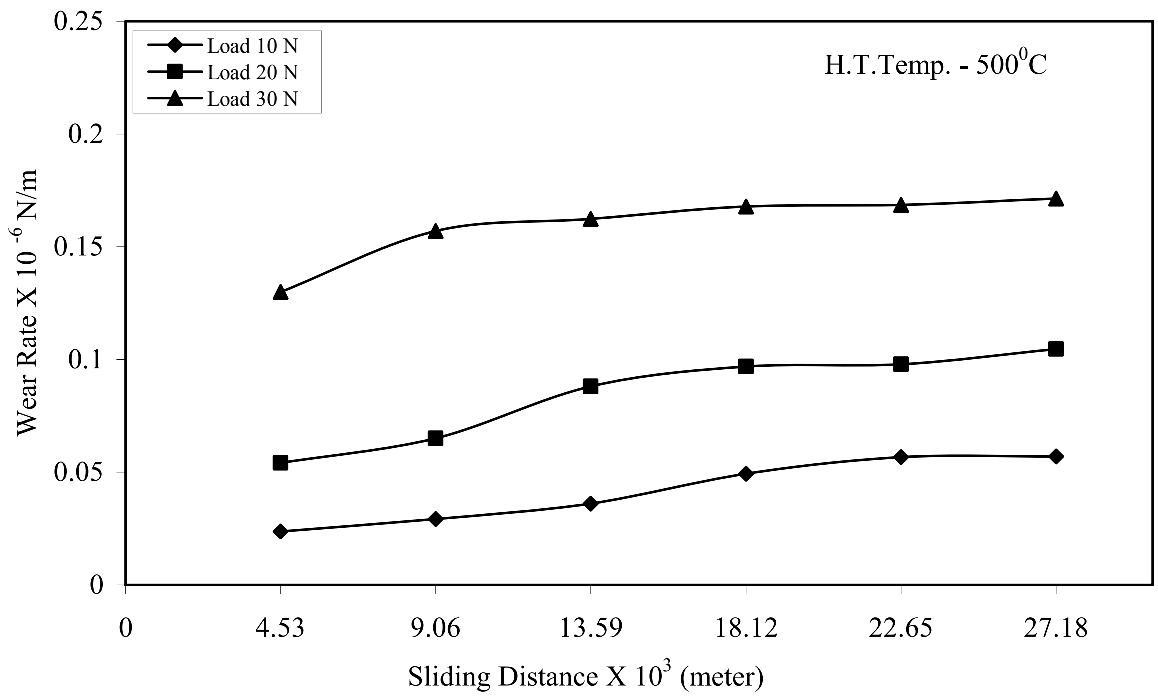


Fig. 4.2(d)

Figs. 4.2 (a-d) Variation of wear rate with sliding distance for normal water quenching.

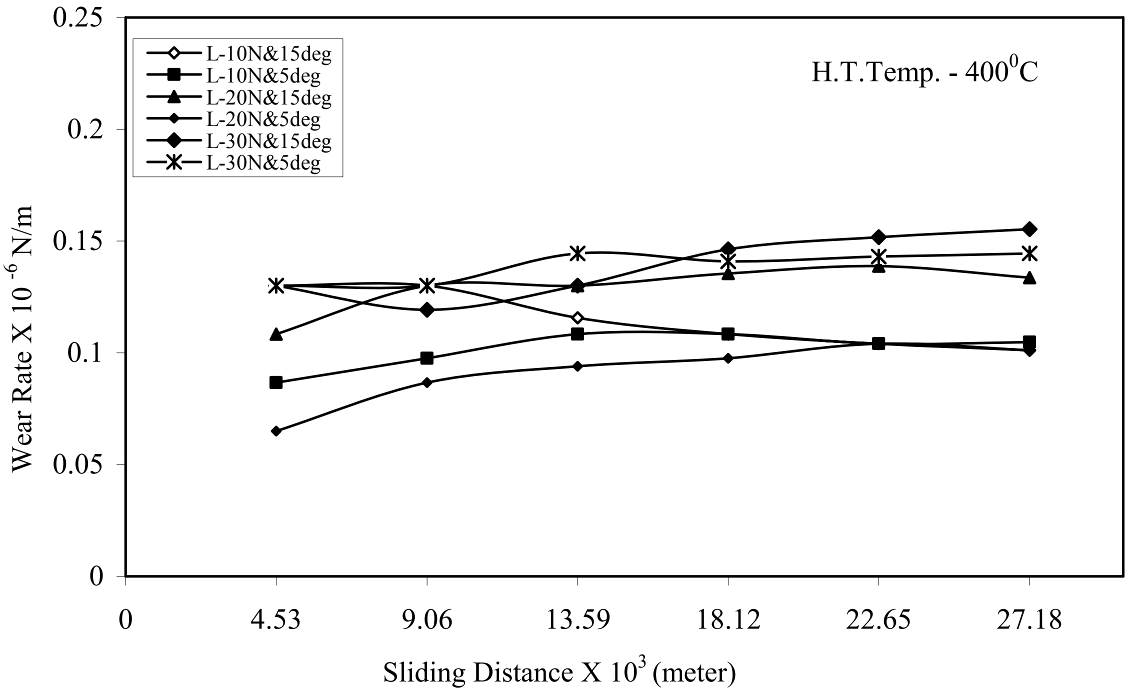


Fig. 4.2 (e)

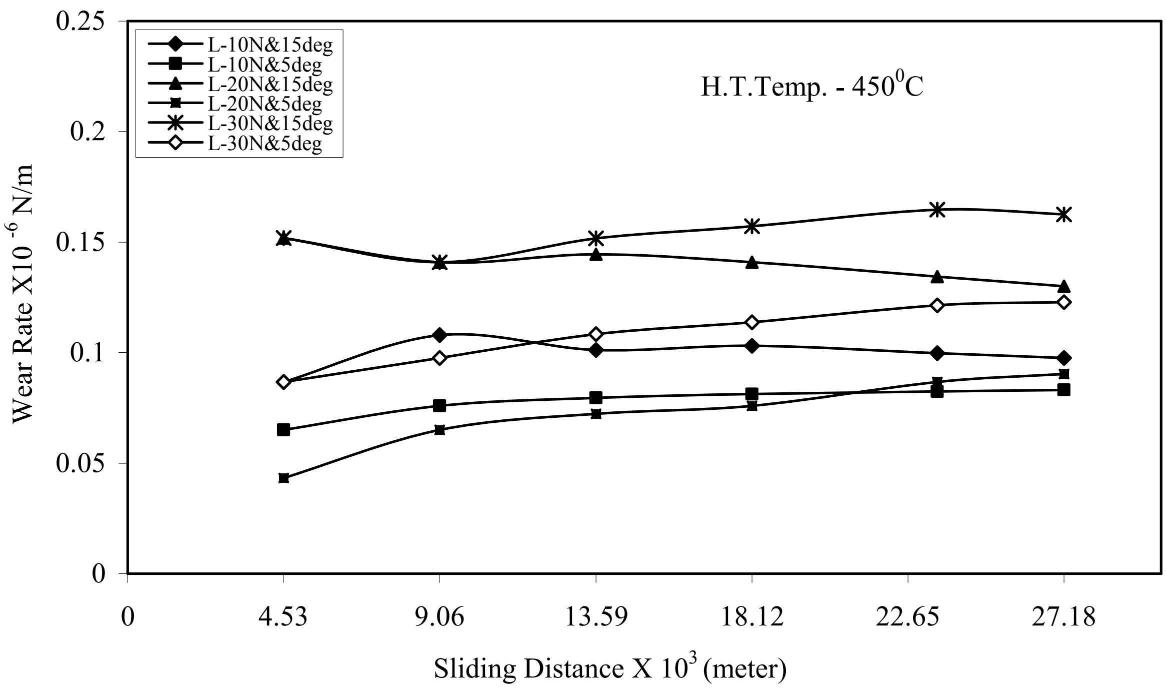


Fig. 4.2 (f)

Figs. 4.2 (e-f) Variation of wear rate with sliding distance for cooling water (15 & 5^{o}C) quenching.

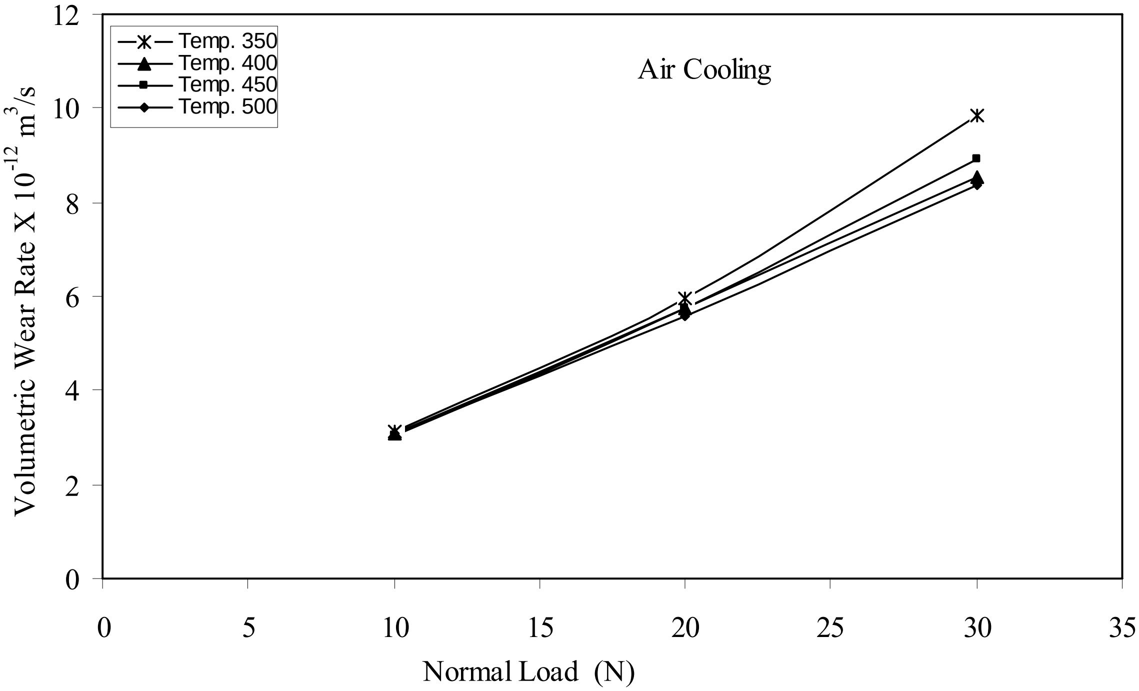


Fig. 4.3 (a)

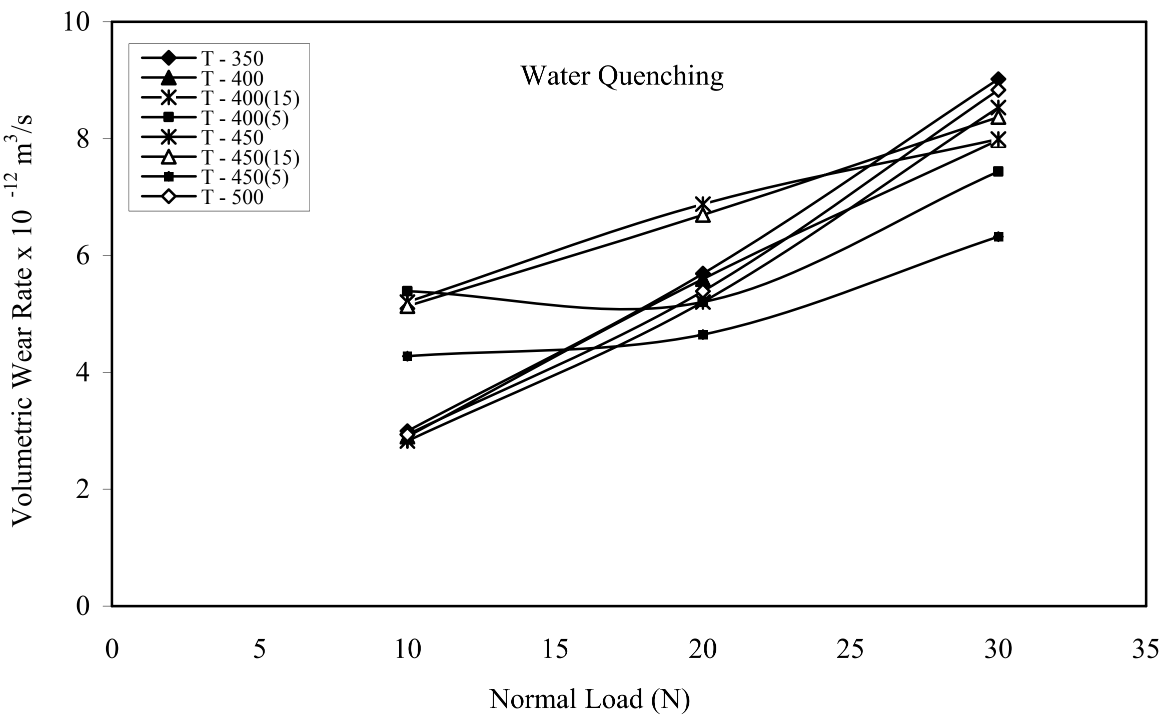


Fig. 4.3 (b)

Figs. 4.3 Variation of volumetric wear rate with normal load for (a) air cooling, & (b) water quenching.

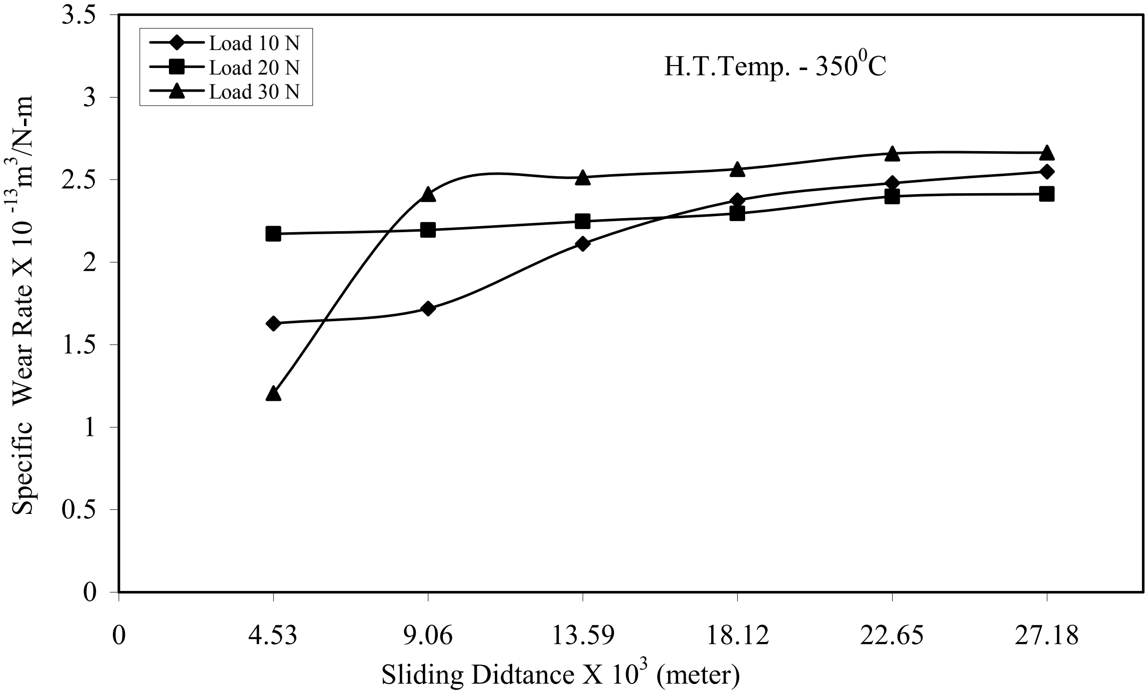


Fig. 4.4 (a)

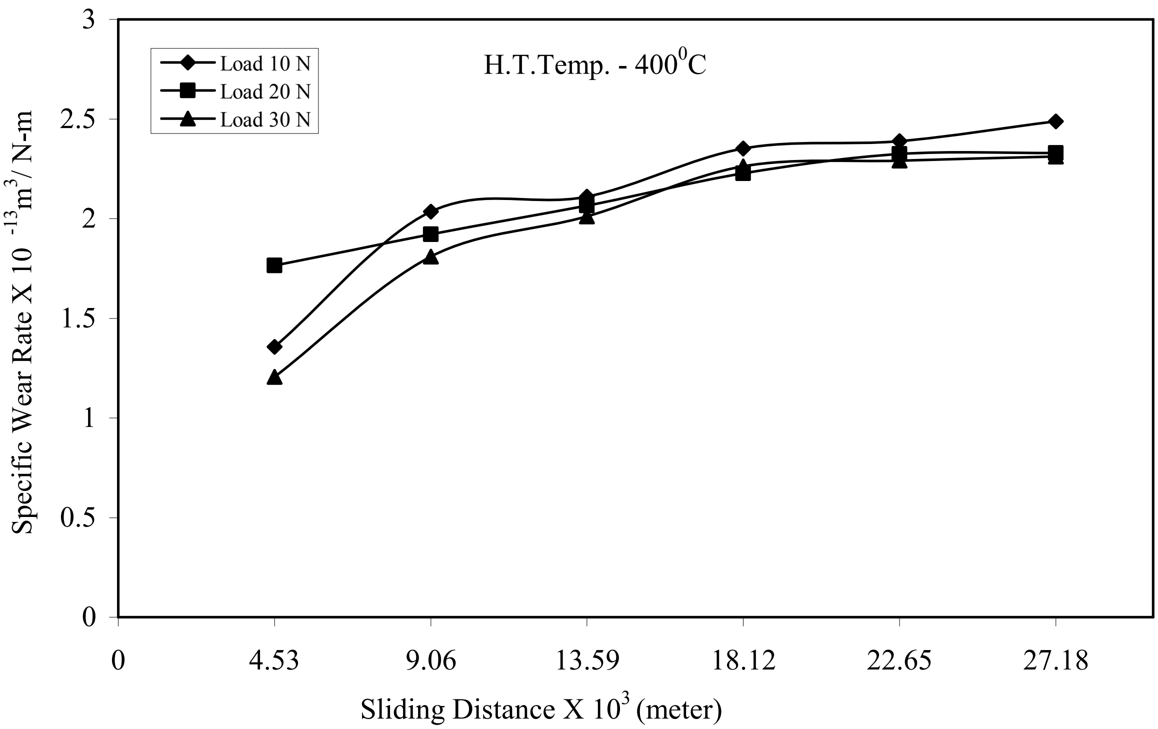


Fig. 4.4 (b)

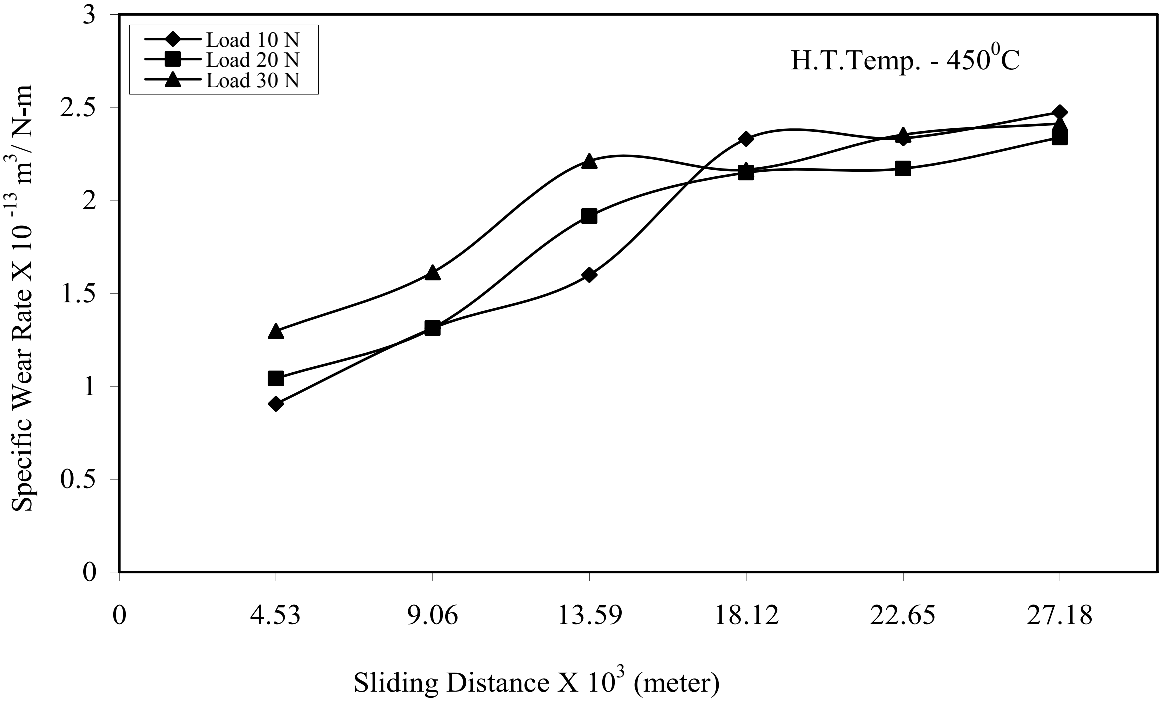


Fig. 4.4 (c)

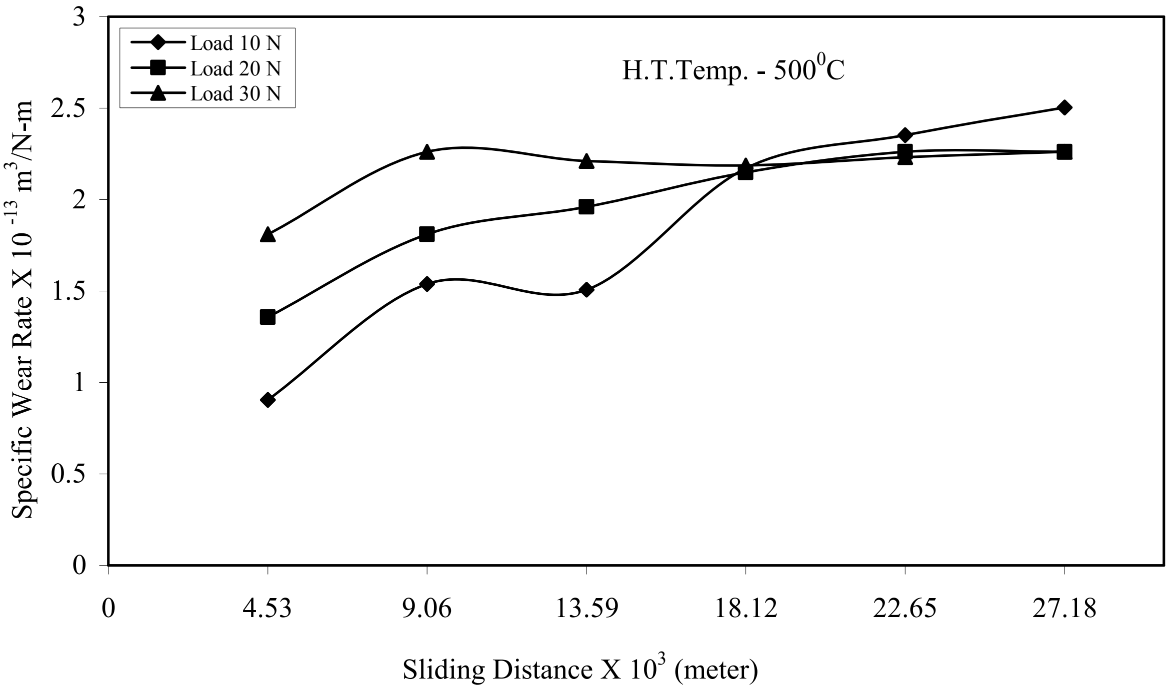


Fig. 4.4 (d)

Figs. 4.4 (a-d) Variation of specific wear rate with sliding distance for air cooling.

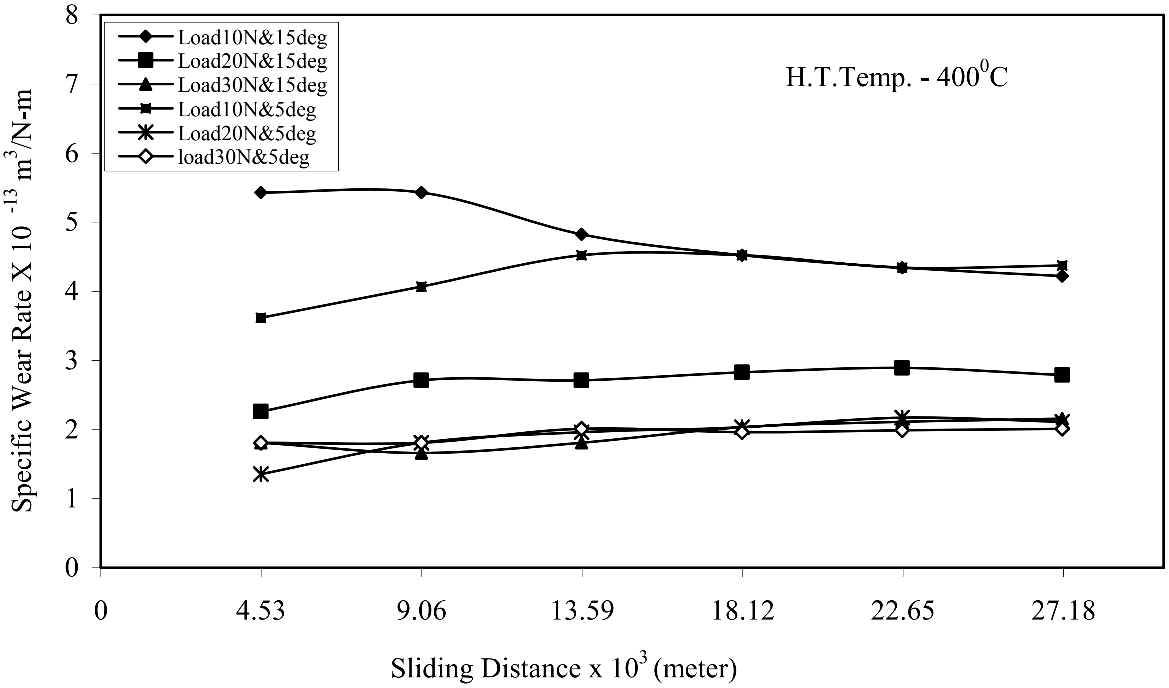


Fig. 4.5 (a)

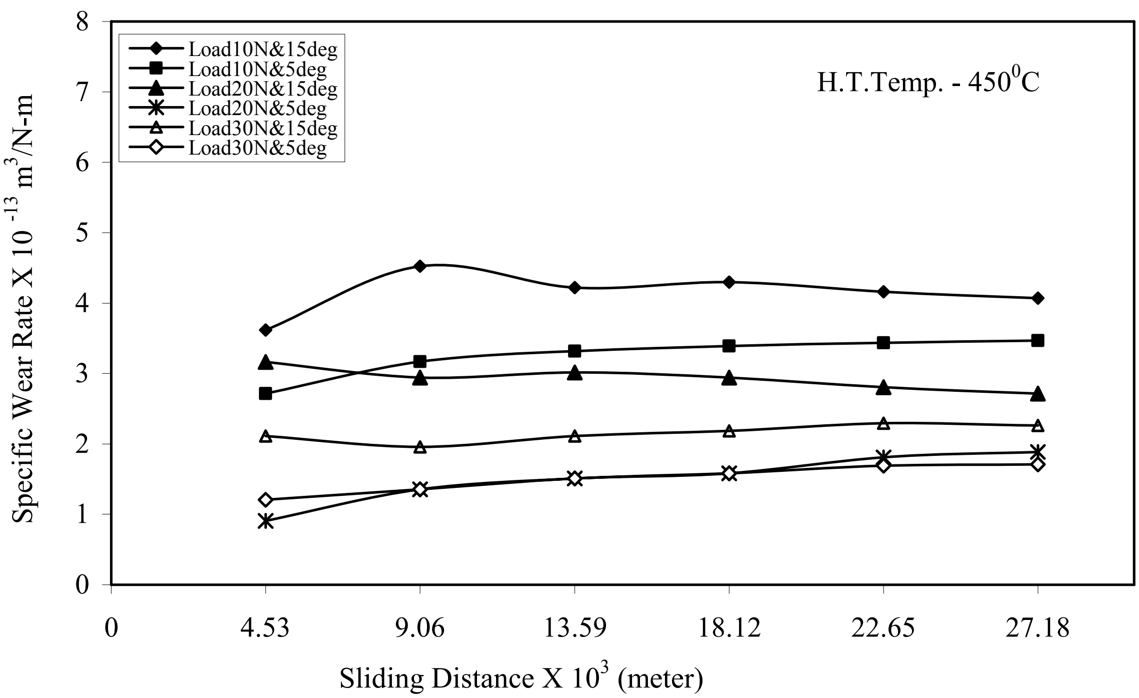


Fig. 4.5 (b)

Figs. 4.5 (a-b) Variation of specific wear rate with sliding distance for cooling water quenching.

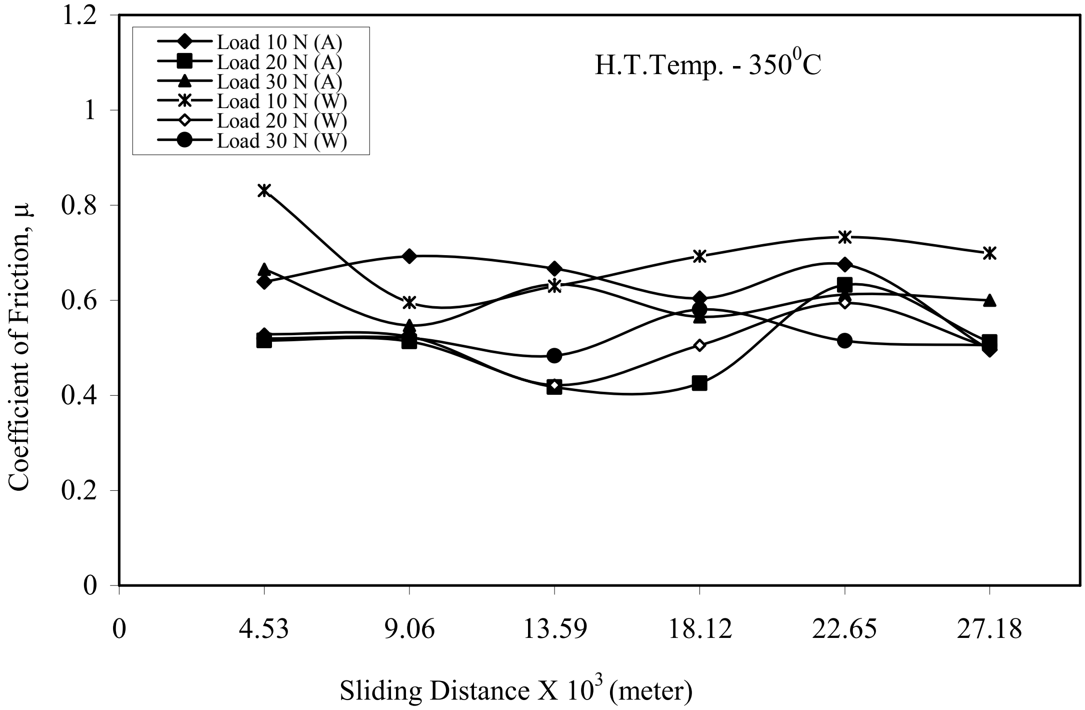


Fig. 4.6 (a)

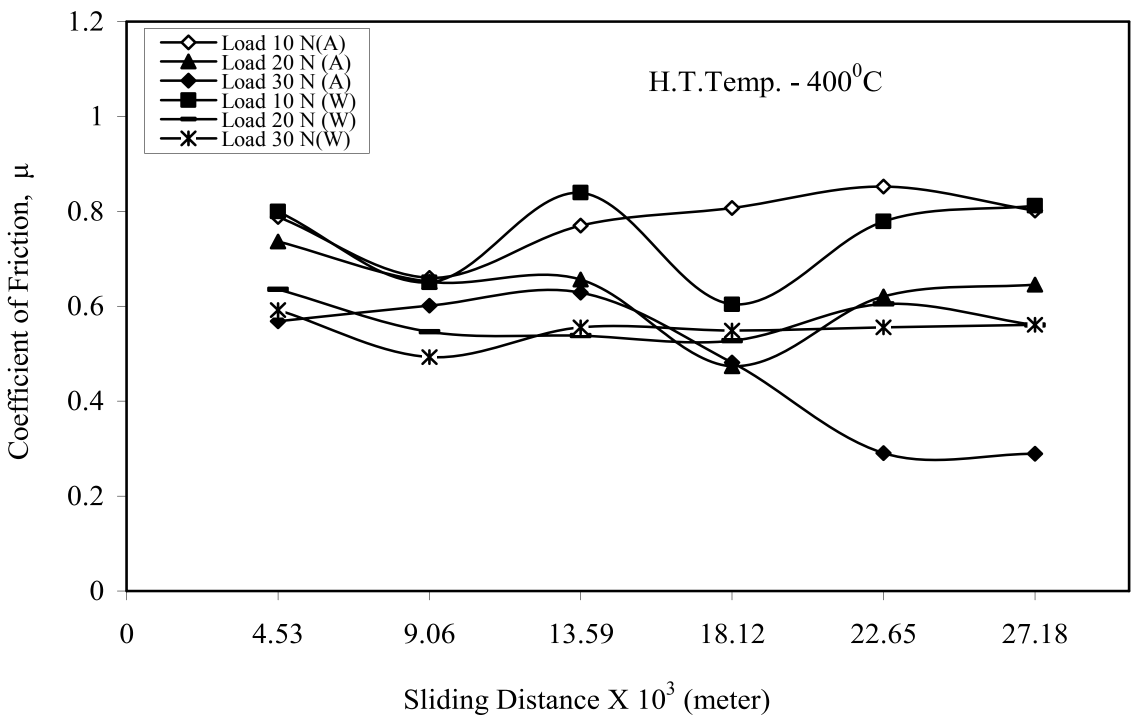


Fig. 4.6 (b)

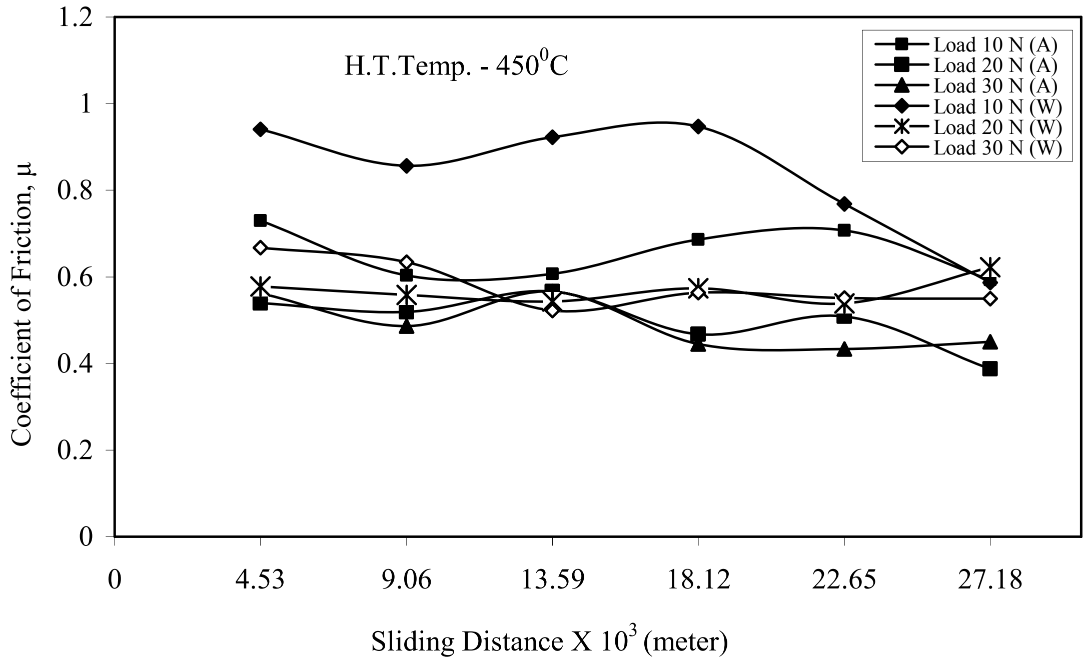


Fig. 4.6 (c)

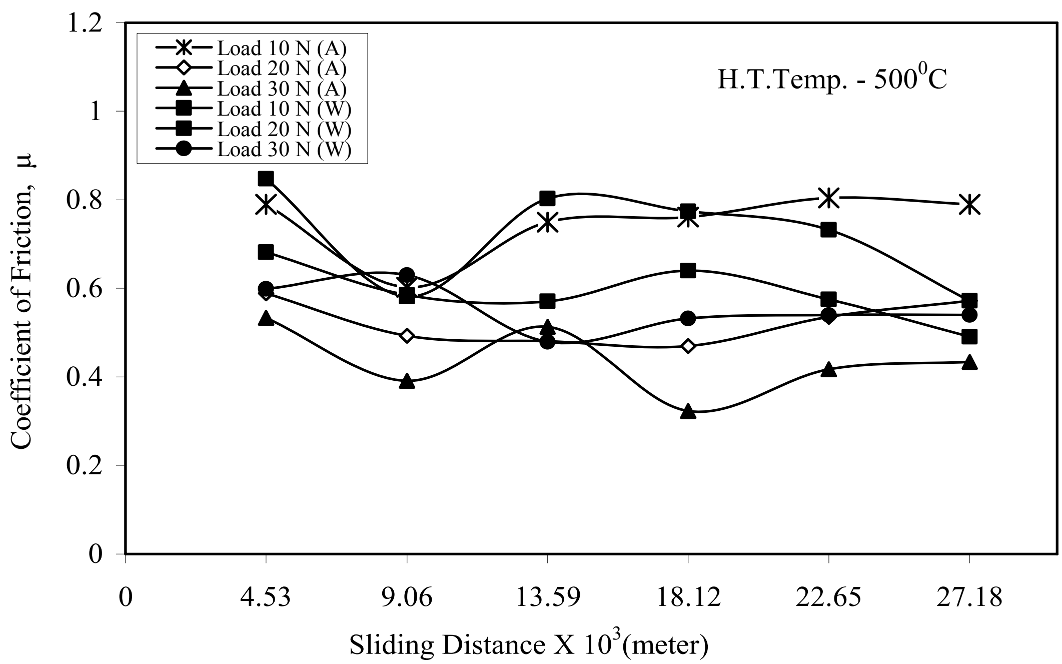


Fig. 4.6 (d)

Figs. 4.6 (a-d) Variation of coefficient of friction with sliding distance for different heat treated temperatures.

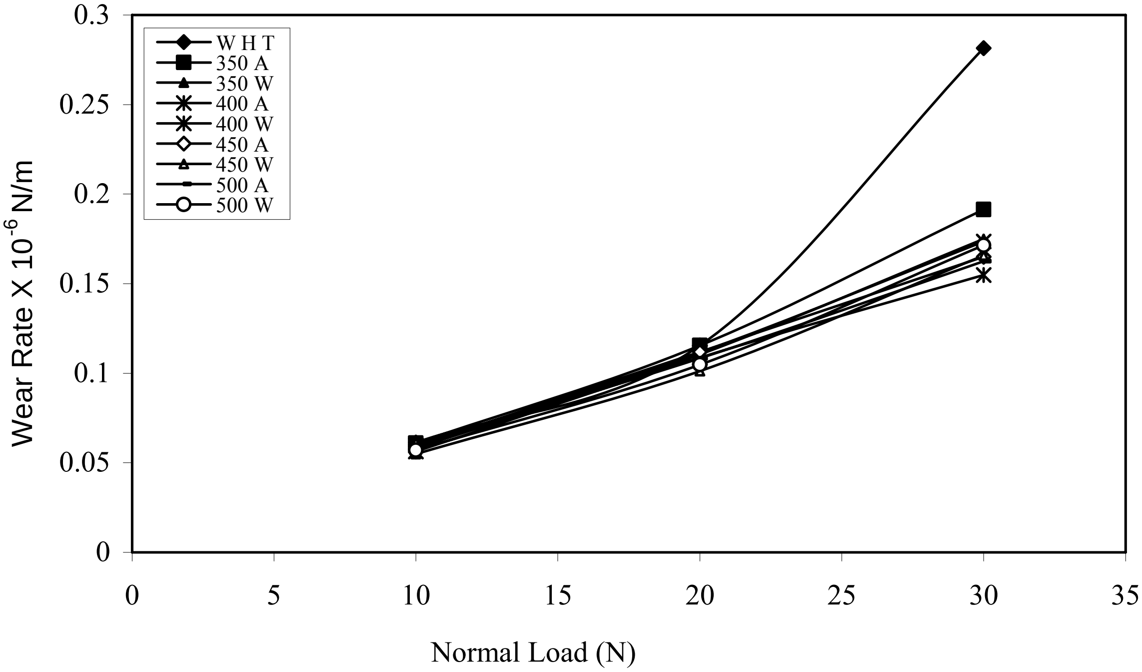


Fig. 4.7 (a) Comparison of wear rate with and without heat treatment for air cooling and normal water (25^0C) quenching.

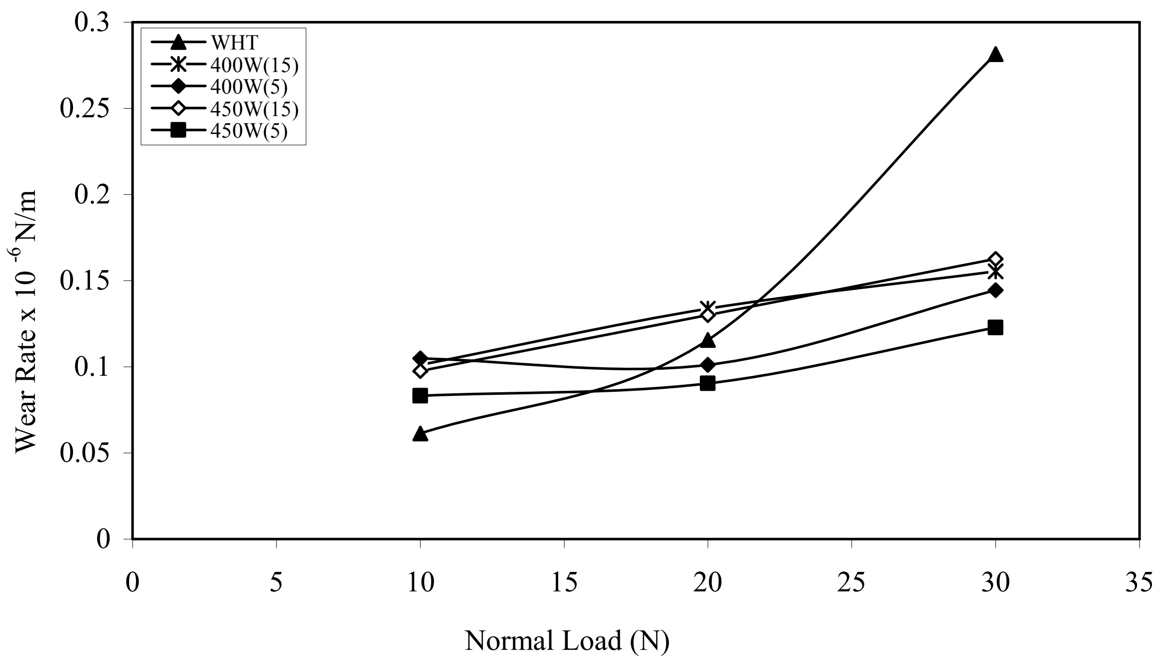


Fig. 4.7 (b) Comparison of wear rate with and without heat treatment for cooling water (15 & 5^0C) quenching.

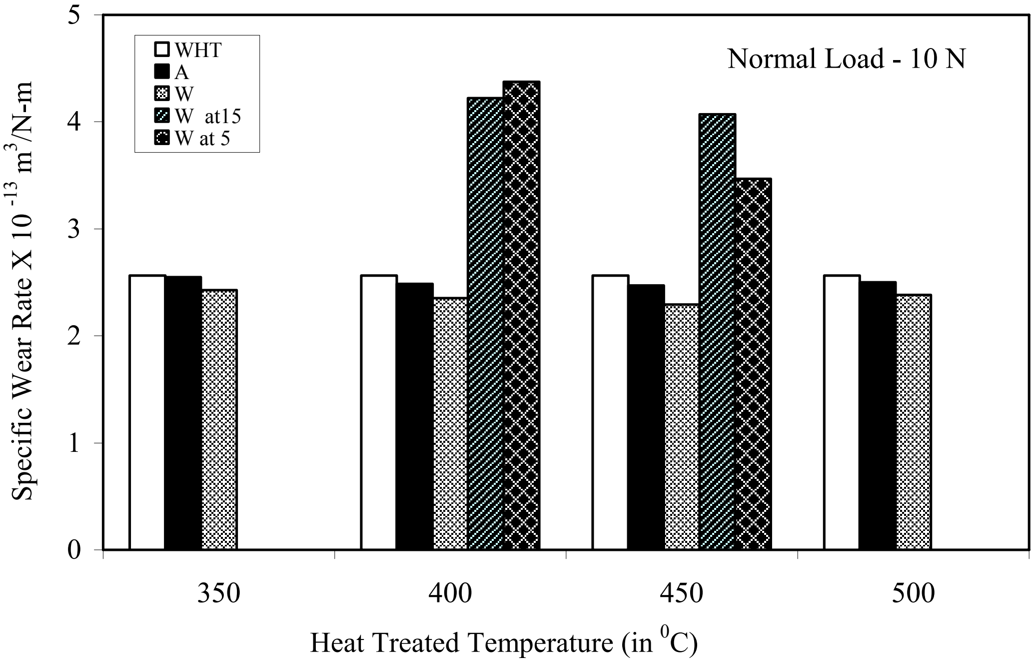


Fig. 4.8 (a)

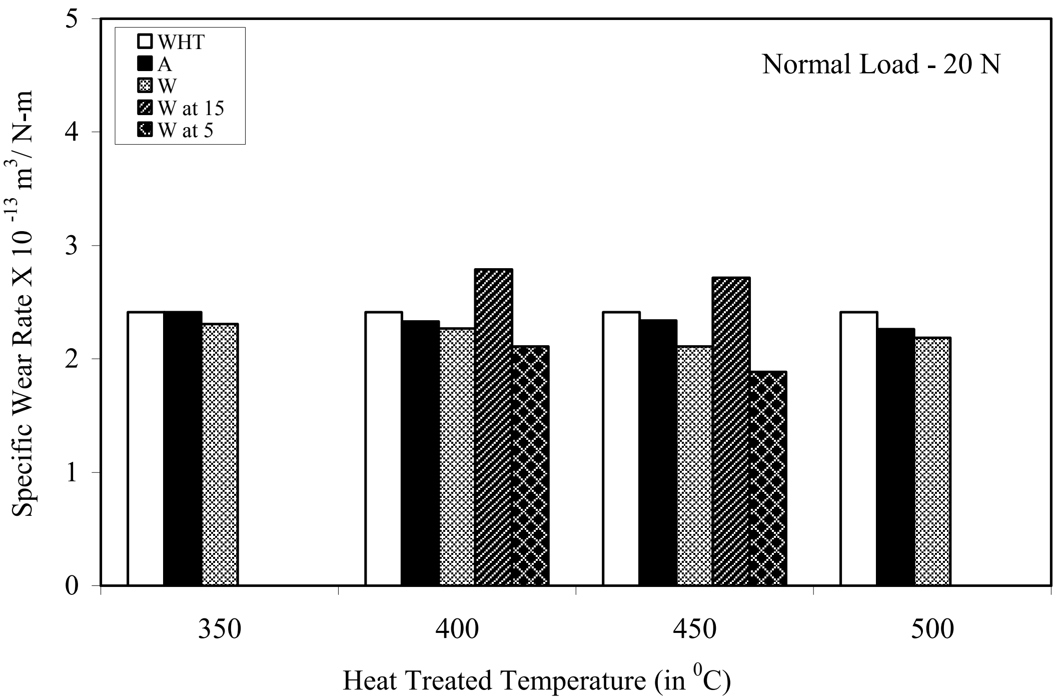


Fig. 4.8 (b)

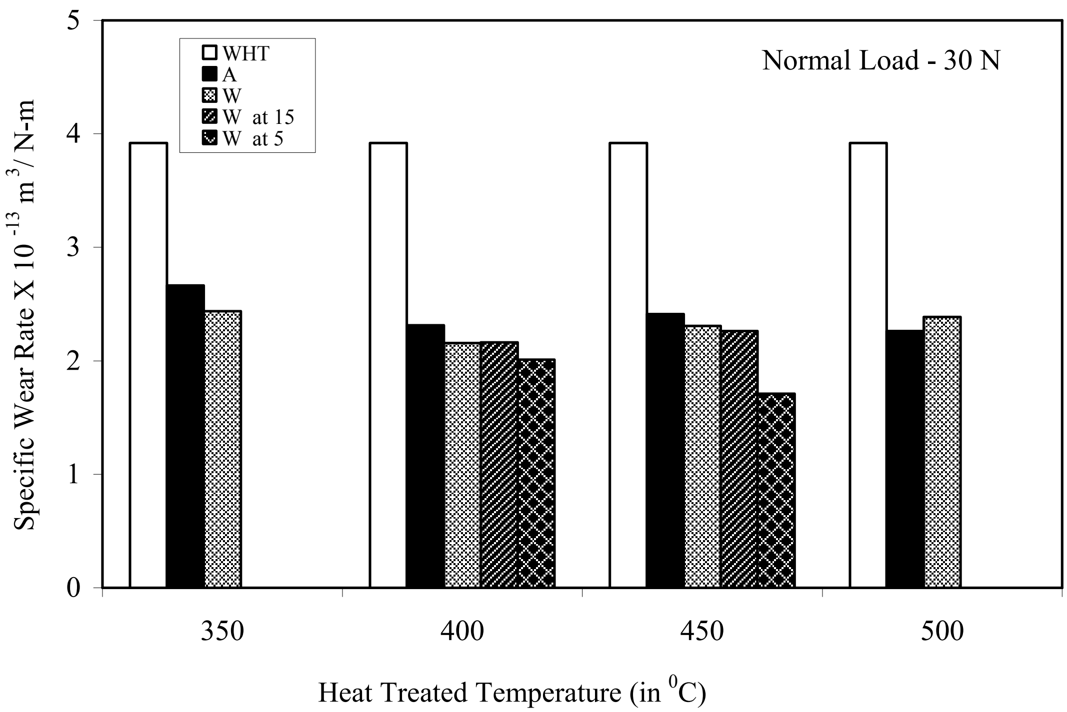
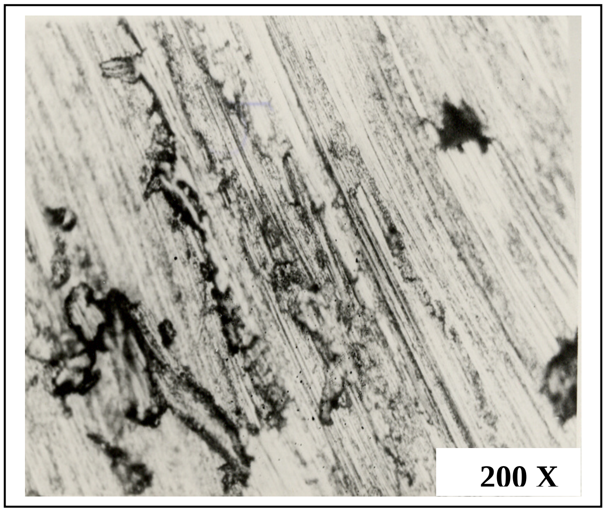


Fig. 4.8 (c)

Figs.4.8 (a-c) Comparison of specific wear rate with and without heat treatment for different loads

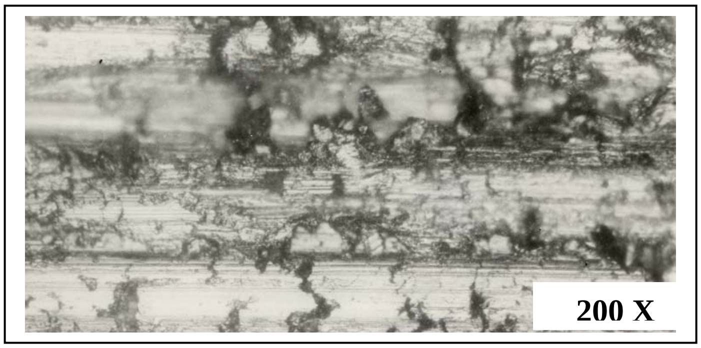


(a)

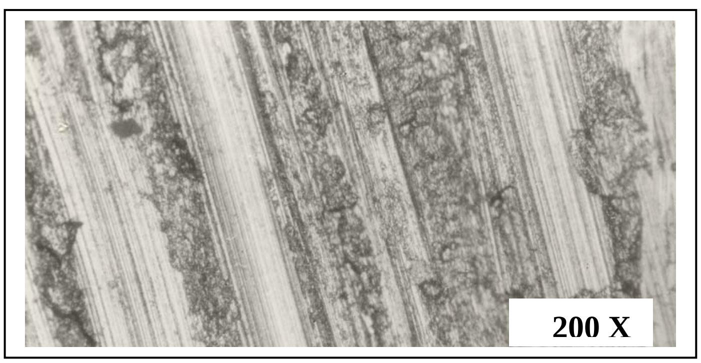
(b)

Figs. 4.9 Micrographs showing wear surface of heat treated samples for air cooling (a) load 30N & temperature 350^{0}C
(b) load 30N & temperature 450^{0}C

(a)



(b)



(c)

Figs.4.10 Micrographs showing wear surface of heat treated samples for water quenching (a) load 10N, temp. 450^{0}C & quenching water temp. 15^{0}C
(b) load 20N, temp. 450^{0}C & quenching water temp. 5^{0}C
(c) load 30N, temp. 450^{0}C & quenching water temp. 5^{0}C.

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CHAPTER – 5

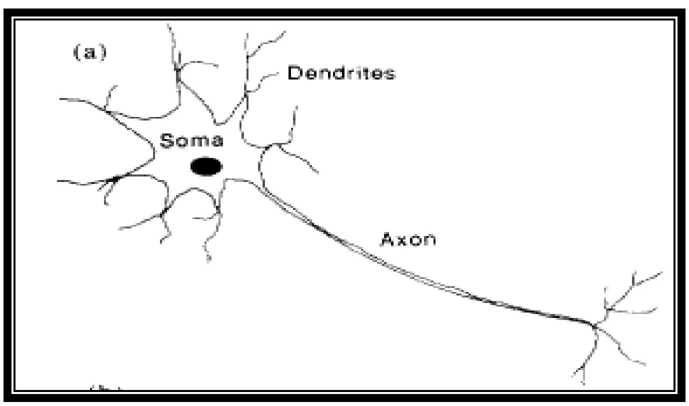
PREDICTION OF WEAR BY USING NEURAL NETWORKS

5.1 INTRODUCTION

An artificial neural network is a parallel distributed information processing system. ANN (Artificial Neural Network) is developed in the model of human brain. A brief description is included in the following section.

Biological neurons

The structure and the functioning of the human brain have been studied by many neurophysiologists. However, only an overview of it is available at present. Basically the brain functions with a very dense network of neurons. Fig 5.1 (a) below indicates a typical biological neuron. The brain contains as many as 10^{11} neurons connected to each other by as many as 10^{15} interconnections among them.



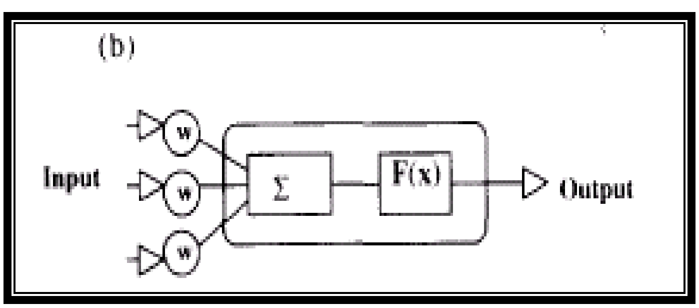


Fig 5.1 (a) A biological neuron (b) An artificial neuron

A neuron consists mainly of the following parts:

The cell body

The axon

The dendrite

The dendrite is responsible for carrying the signals from various other neurons to the neuron of which it is a part. These dendrites are spread in a branched form to carry complex electro-chemical signals. On the other hand, an axon carries the signal from the cell body to various other neurons. When many dendrites carry signals to the cell body they are essentially accumulated there. After a sufficient time a signal is generated by the cell body and the same is sent down by the axon if the accumulation exceeds a threshold. The biological neural network also demonstrates various other behaviors which are very difficult to simulate using presently available hardware and software. Hence the neural units in the artificial neural network are developed as a very approximate model of the biological neurons.

Artificial neurons

An artificial neuron can carry out a simple mathematical operation and or can compare two values. Fig 5.1(b) describes an artificial neuron gets input from other neurons or directly from the environment. The path connecting two neurons is associated with a certain variable weight which represents the synaptic strength of the connection. The input to a neuron from another neuron is obtained by multiplying the output of the connected neuron by the synaptic strength of the connection between them. The artificial neuron then sums up all the weighted inputs coming to it.

$$x_j = \sum_{i=1}^{m} w_{ij} o_i \qquad \text{-------------------} \quad (5.1)$$

Where X_j = summation of all the inputs for neuron j

W_{ij} = synaptic strength between neuron i and neuron j

O_i = output of neuron i

m = total number of neurons sending input to neuron j

Each neuron is associated with a threshold value and a squashing function. The squashing function is used to compare the weighted sum of inputs and the threshold value of that neuron. If the threshold value is exceeded by the weighted sum the neuron goes to a higher state, i.e. the output of the neuron becomes high. Different squashing functions are used in different applications. In the present work a back propagation learning algorithm has been used.

The output of the neuron for a given input can be controlled to a desired value by adjusting the synaptic strengths and the threshold values of the neuron. In an artificial neural network (ANN) several neurons can be connected in variety of ways. Many different types of neural nets have been developed [200]. The network architecture has to be selected keeping the problem at hand in mind. For the present investigation a feed forward network is most suitable.

5.2 FEED FORWARD NETWORK

In a feed forward network the neural units are classified into different layers. The network consists of one input layer, one or two hidden layers and one

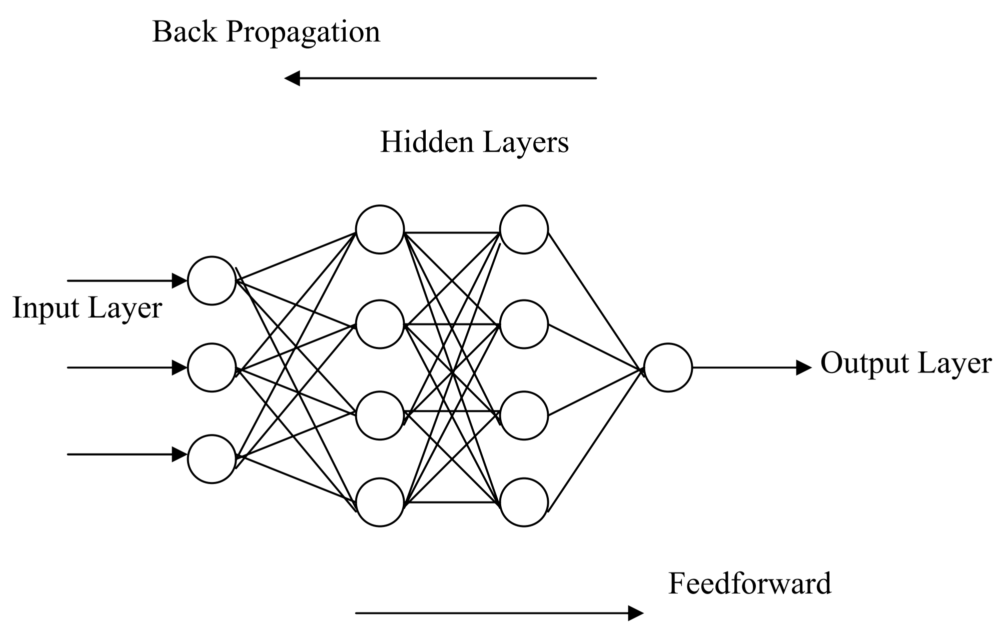


Fig.5.2 A feed forward network

output layer of neurons. Fig.5.2 presents a typical feed forward network. It may be noted that all the neurons between two successive layers are fully connected, i.e. each neuron of a layer is connected to each neuron of neighboring layers. However, there is no connection between neurons of the same layers. The input layer receives input information and passes it onto the neurons of the hidden layer(s), which in turn pass the information to the output layer. The output from the output layer is the prediction of the net for the corresponding input supplied at the input nodes. Each neuron in the network behaves in the same way. There is no reliable method for deciding the numbers of neural units require for a particular problem. This is decided based on experience and a few trials are required to determine the best configuration of the net.

In a feed forward network the knowledge is stored in a distributed manner, in the form of synaptic strengths and thresholds. Thus it can generalized, i.e. it may be used for the situations for which the net has not been trained. Initially, the synaptic strengths and the threshold values are allocated randomly. To train the network for a specific knowledge a set of training examples are prepared. A training example consists of a set of values for the input neurons and the corresponding values for the output neurons. Several of such input- output pairs are to be prepared carefully to reflect all the aspects that the net needs to learn. All the training examples together form the training set. In the beginning of the training process, as the synaptic strengths and threshold are selected randomly the output predicted by the net for a particular input and the output supplied in the corresponding training examples may not match. However, the synaptic strengths and the thresholds can be adjusted so that the net predicts the output correctly. As several examples are to be learnt by the net there must be a sufficient number of neural units in the net. The adjustments in the synaptic strengths and thresholds are carried out following a learning algorithm. The back propagation algorithm has been used in the present work for this purpose.

The back Propagation algorithm

The back propagation algorithm is a generalized form of the least mean square training algorithm for perceptron learning [201,202]. It uses the gradient search method to minimize the error function which is the mean square difference between the desired and the predicted output. The error for the p^{th} example is given by

$$E_p = \sum_i (d_j - o_j)^2 \quad \text{-----------------------} \quad (5.2)$$

Where d_j = the output desired at neuron j and o_j = the actual output of neuron j.

$$O_j = f(ß_j) = f\left(\sum_i w_{ij} o_i\right) \quad \text{-----------------------} \quad (5.3)$$

The error can be minimized by moving along the steepest decent direction on the error surface

$$\frac{\partial E}{\partial w_{ij}} = \frac{\partial E}{\partial \beta_j} \frac{\partial \beta_j}{\partial w_{ij}} = \frac{\partial E}{\partial \beta_j} o_i = \delta_j o_i \quad \text{---------------} \quad (5.4)$$

Where δ_j for a neuron is

$$\delta = f'(ß_j) \sum_k \delta_k w_{kj} \quad \text{---------------------------------} \quad (5.5)$$

and f' indicates the first order derivative of the function and k indicates a neuron in the layer which is successive to the layer which contains neuron j. Therefore, the weight matrix can be adjusted recursively for each example

$$w_{ij}(t+1) = w_{ij}(t) + \eta\, \delta_j\, x_i \quad \text{----------------------------} \quad (5.6)$$

Where η is an adjustable gain term which controls the rate of convergence.

The above operation is repeated for each example and for all the neurons until a satisfactory convergence is achieved for all the examples present in the training set.

5.3 NEURAL NETWORKS IN MATERIAL SCIENCE

The feed forward neural networks have been applied to the solution of various engineering problems such as design of equipment and structures, fault detection, management of manufacturing and construction, etc. They have also been effective in computer implementations of natural process such as natural language understanding, speech recognition, pattern recognition, etc. This tool can be utilized very effectively in the solution of problems of material science. The materials are either available in nature or are the product of engineering. The behaviour of the material is best understood by carrying out experiments. Conventionally, the experimentally observed behaviour of a material using is modeled analytically using simple algebraic expressions. The analytical expression should predict the material behaviour which agrees closely with the experimental observations. However, it may not always be possible to capture every material behaviour by means of a simple expression. The development of such expressions can be extremely difficult and time consuming. Moreover, the behaviour of modern materials is becoming more and more complicated and they demand a more detailed study. The feedforward neural networks can be extremely helpful in capturing the experimentally observed material behaviour directly which precludes the necessity of developing analytical expressions. The neural networks generalize on their own. Therefore, they are also effective in predicting the behaviour of a new material before the material is produced in the laboratory. This may reduce the cost of expensive experiments.

ANN for Prediction of Wear

Very few works have been reported for modeling and prediction of wear properties of MMCs by using ANN technique.

K.Velten [203], Jones [204], K.Genel [205] have used different ANN models in tribological applications. Their modeling results confirm the feasibility of ANN and its good co-relation with the experimental results. Rosit Koker [206], S. Schmauder [207] used ANN technique for finding out the properties of different MMCs. They have the opinion that ANN is a powerful tool to predict the properties of MMCs if it is properly trained. Wear is not an intrinsic material property but characteristics of the engineering system which depend on load, speed, temperature, hardness, presence of foreign material and environmental conditions. Experiments have been successfully completed and have already been discussed in chapter - 3 & 4. In this present investigation attempt has been made to confirm the applicability of ANN techniques for prediction of Wear of MMC by comparing the results of ANN with the experimental results.

In this study, the back propagation which is a widely used algorithm is used in training. It can map non linear process. It is a feed forward network with one or more hidden layers. The elementary architecture of the back propagation network has three layers. There are no constraints about the number of hidden layers. Back propagation is a systematic method of training multiplayer artificial neural networks. Several applications of artificial neural network for modeling of non linear process system and subsequent control have been reported by Bhat and Mc.Avoy [208] and Singh and Mohanty [209].

In the present investigation, a software package developed by Rao & Rao [210] has been used for predicting the wear behaviour of aluminium red mud composite. The four layered ANN structure used for the present study is shown in Fig. 5.3.

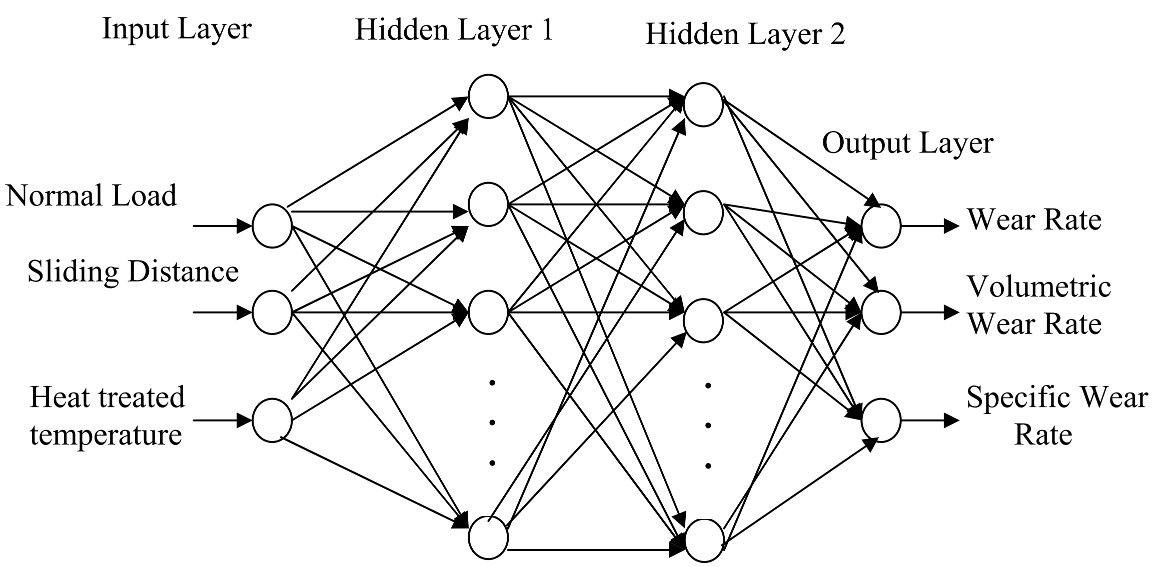


Fig.5.3 Structure of four Layered Neural

Validation of the system

From the original process data two neural networks were tested with fifty nine data sets. Neural net work-1 was used for air & water cooled samples where as network II was used for water cooled at 15 and 5^0 C respectively. Each data set contained inputs such as normal load, sliding distance, heat treated temperatures and an out put values (wear rate, volumetric wear rate and specific wear rate) were returned by the prediction neural network. Training parameters used for network I and II are shown in table 5.1 and 5.2.

5.4 RESULTS & DISCUSSIONS

The Predicted values of wear rate, volumetric wear rate, & specific wear rate with normal load for different heat treated temperatures are shown in Figs.5.4 (a-d), 5.5 (a-d), and 5.6 (a-d). Dotted line refers to neural network results and solid line refers to experimental results. It is seen from these figures that the predicted values are coinciding with the experimental values with mean relative error varying between 4 to 0.46 percent. Hence the predicted results can be acceptable.

5.5 CONCLUSION

In this work, a neural network is designed to predict the volumetric, specific, and wear rate of the particle reinforced aluminium matrix composite according to given volume percent of red mud particles. This study has shown the capability of ANN to predict the wear properties of aluminium red mud composite. It can be concluded that ANN is a good analytical tool that has potential used in the field of tribology if properly used. The well trained neural network provides more useful data from relatively small experimental data base and also can be used to know the results of the critical and large operating conditions.

Table - 5.1

Training parameters used in Prediction Neural Network – I

Training input parameters	Values
Error tolerance	0.01
Learning parameter	0.01
Momentum coefficient	0.001
Noise factor	0.001
Cycles	500000
Slope parameter of sigmoid function	0.6
Hidden layer	2
Number of inputs	3
Number of hidden layer neurons	12
Number of output	3

Table - 5.2

Training parameters used in Prediction Neural Network – II

Training input parameters	Values
Error tolerance	0.01
Learning parameter	0.01
Momentum coefficient	0.001
Noise factor	0.001
Cycles	200000
Slope parameter of sigmoid function	0.6
Hidden layer	2
Number of inputs	3
Number of hidden layer neurons	12
Number of output	3

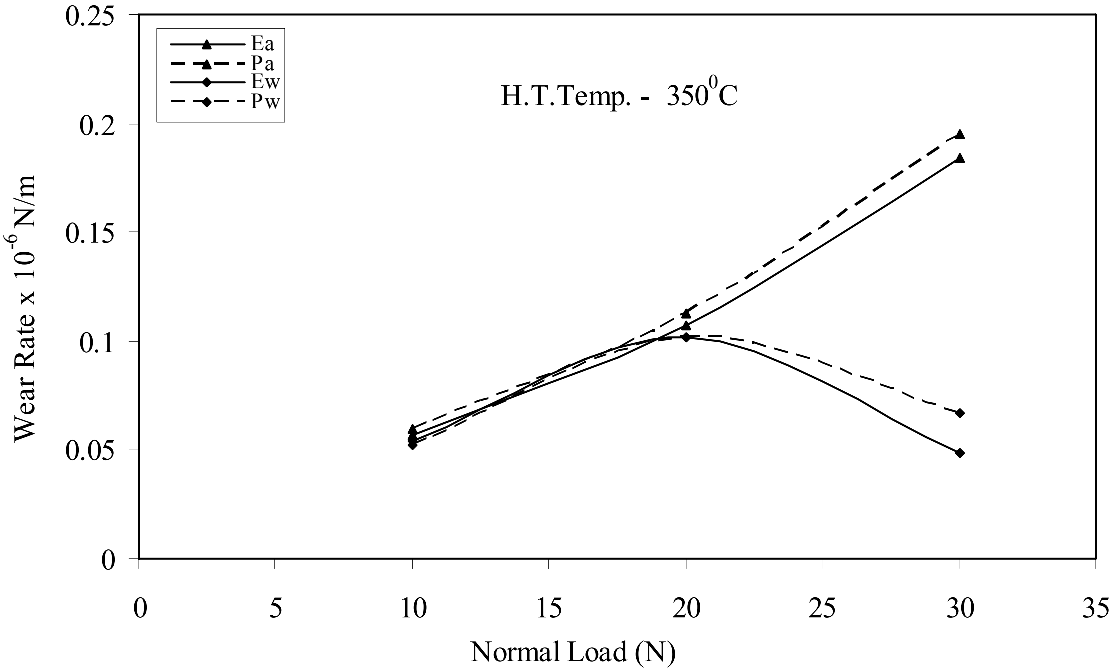


Fig. 5.4 (a)

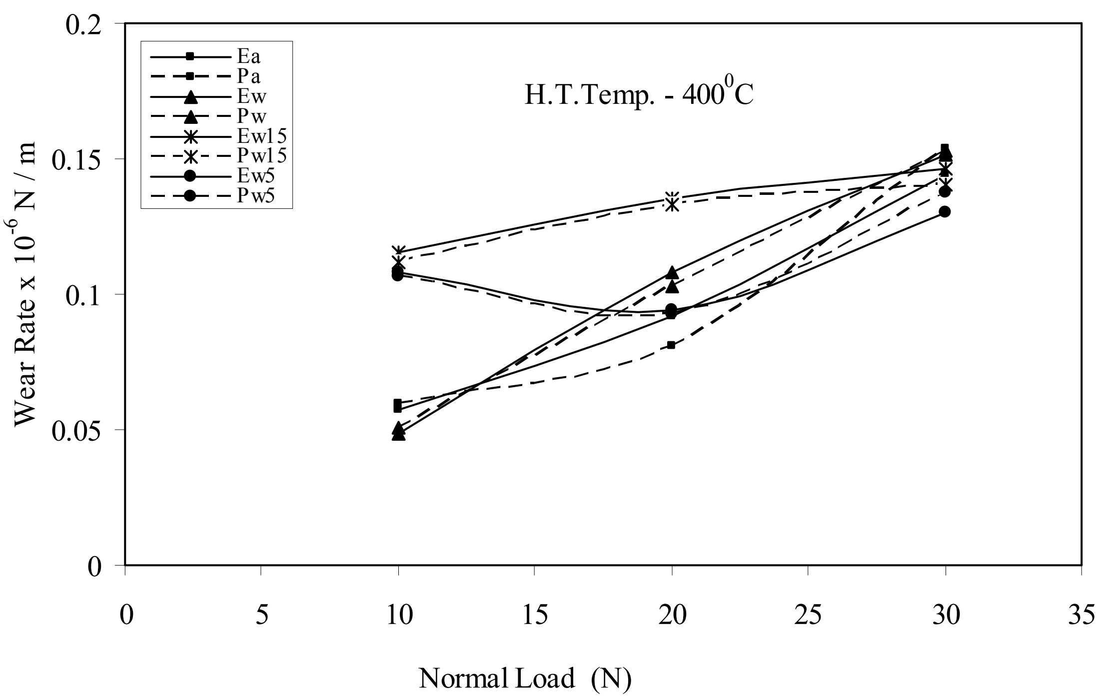


Fig. 5.4 (b)

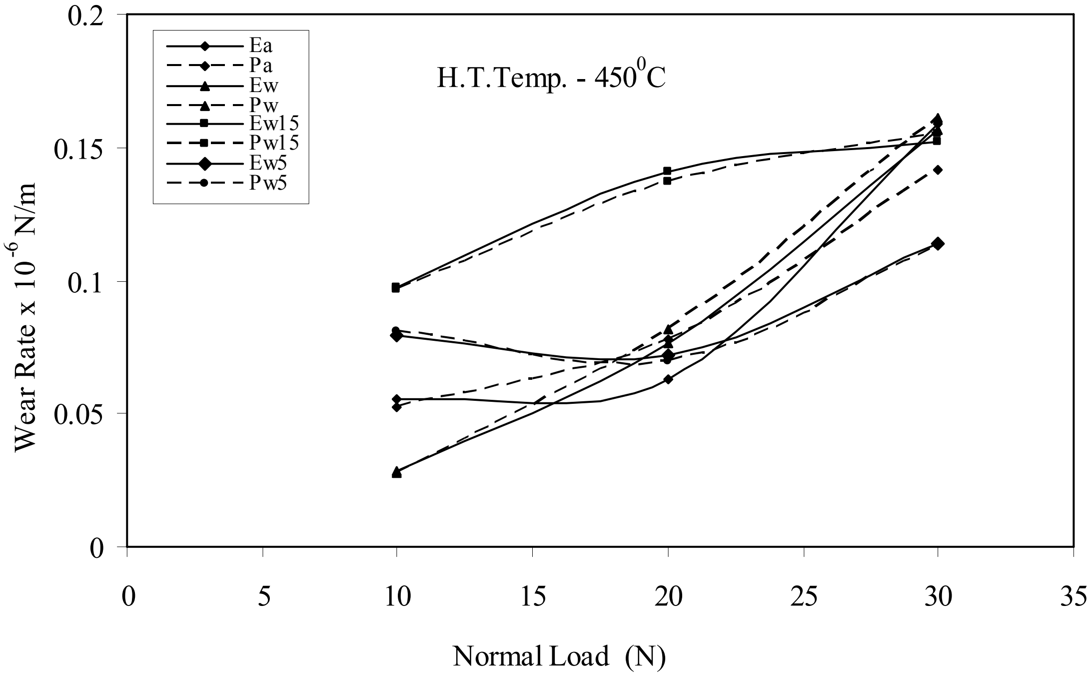


Fig. 5.4 (c)

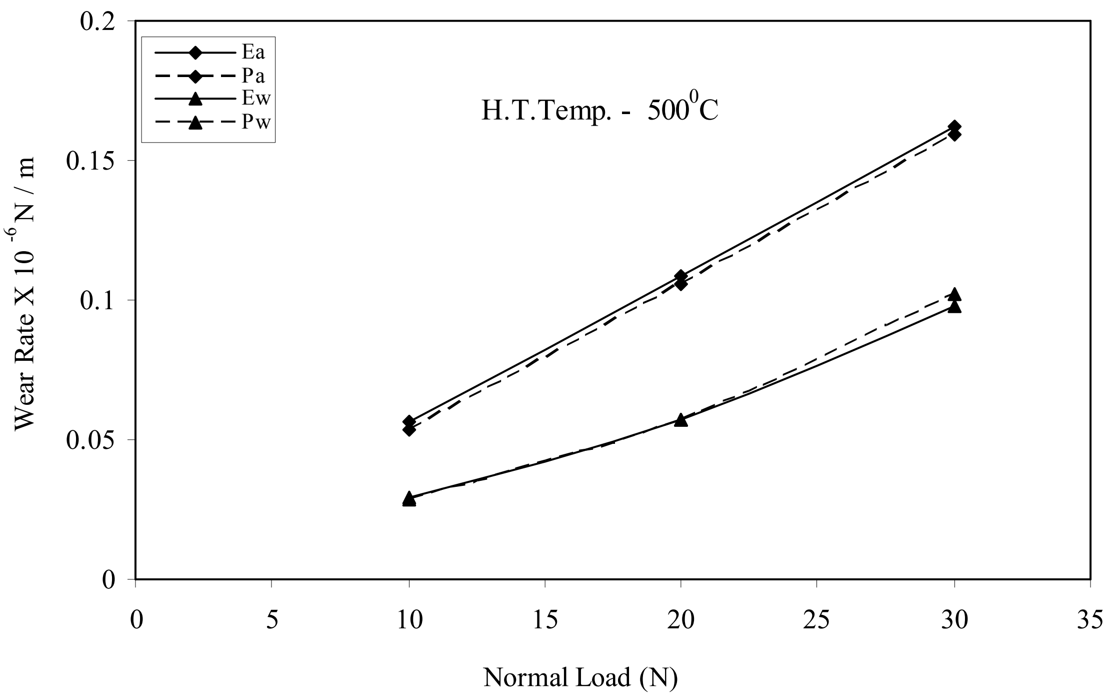


Fig. 5.4 (d)

Figs.5.4 (a-d) Comparison between experimental and predicted values of wear rate with different load (using ANN- I & II).

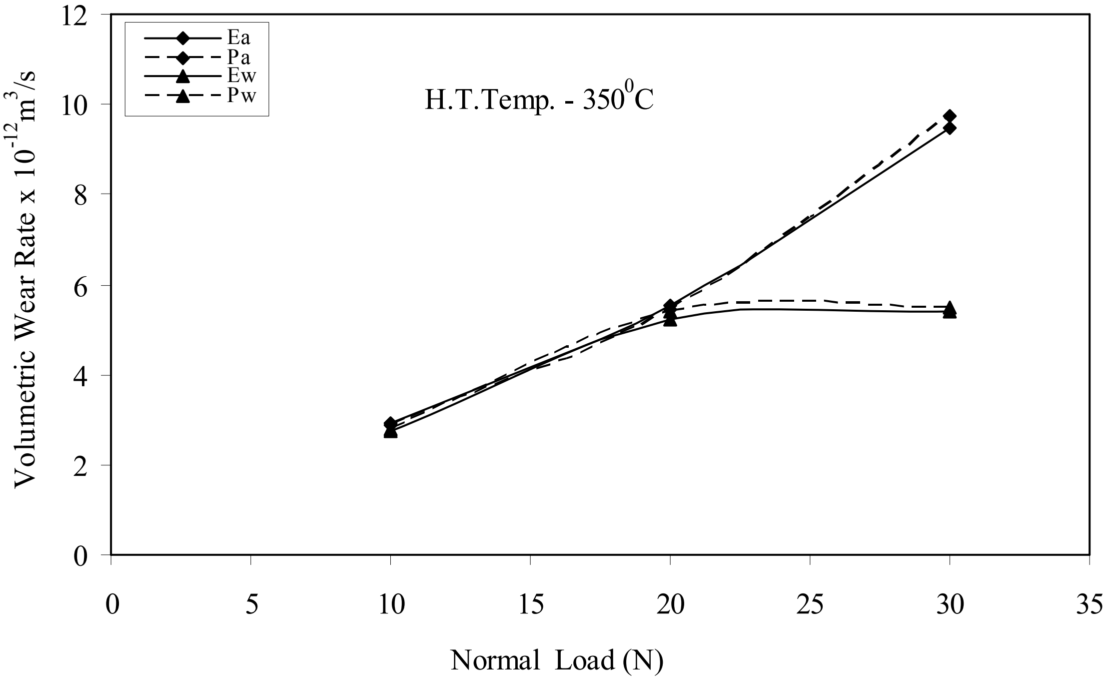


Fig. 5.5 (a)

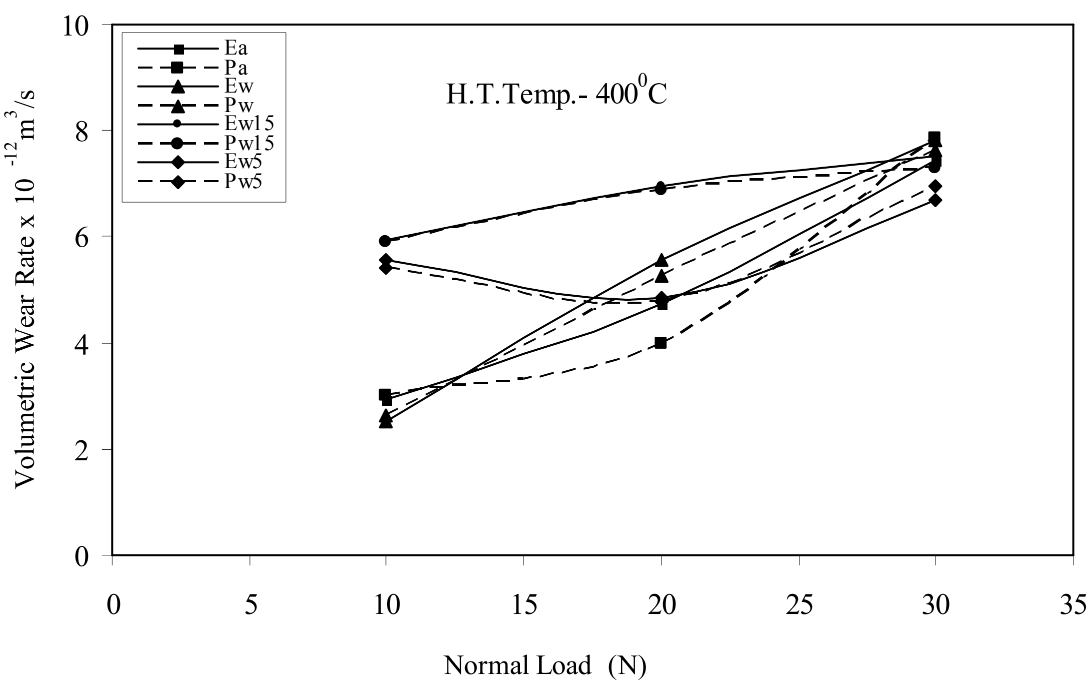


Fig. 5.5 (b)

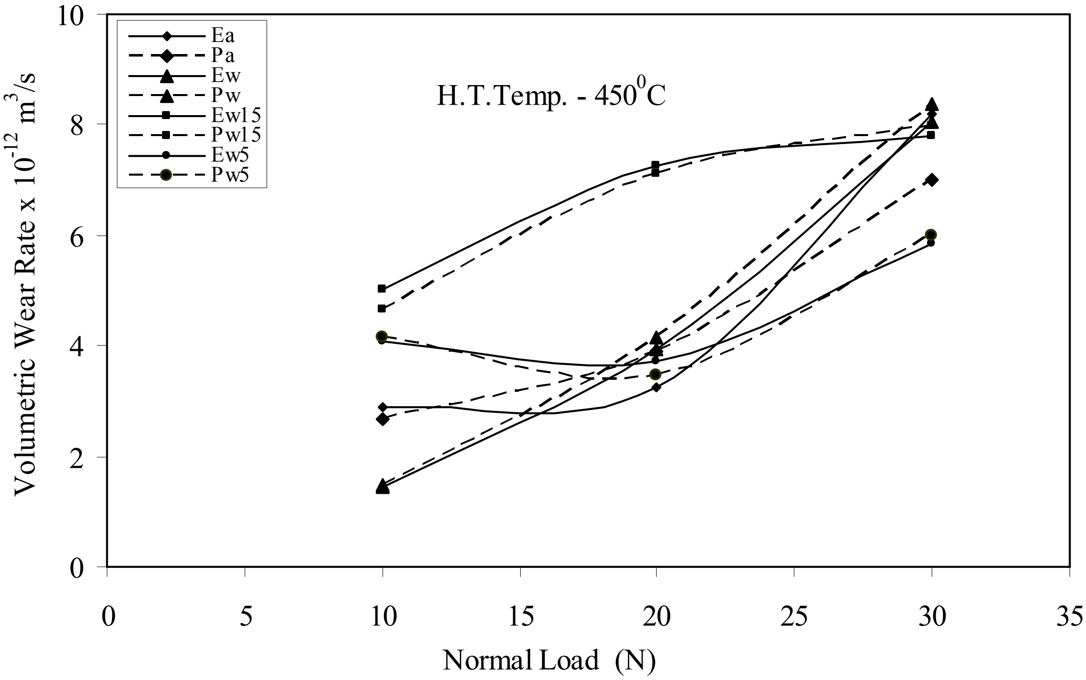


Fig. 5.5 (c)

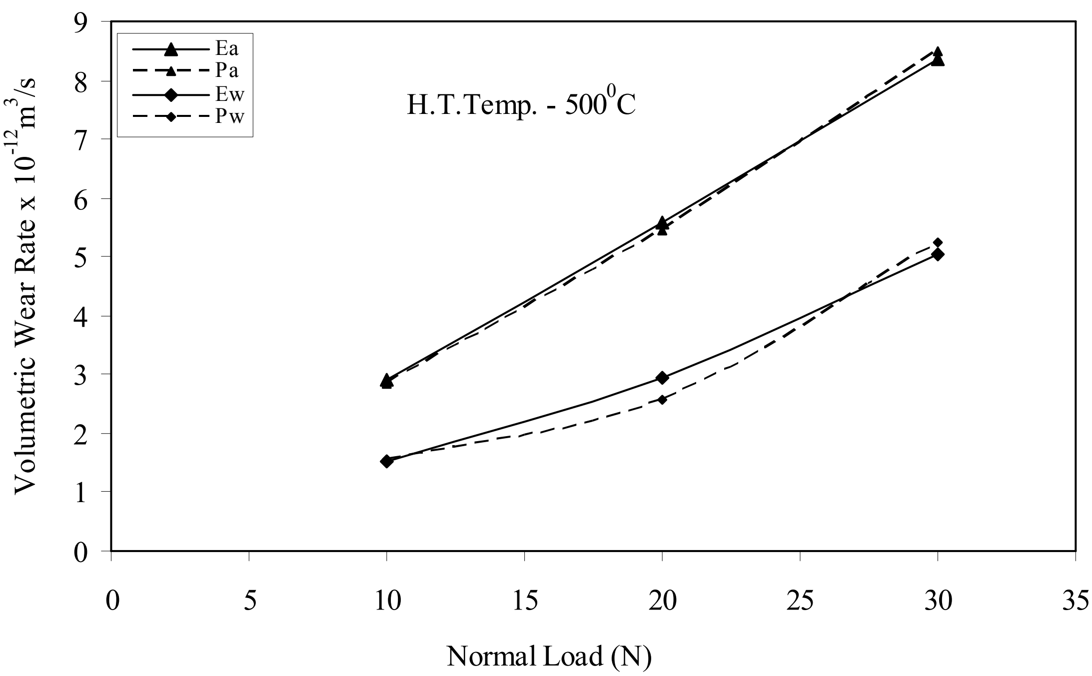


Fig. 5.5 (d)

Fig. 5.5(a-d) Comparison between experimental and predicted values of volumetric wear rate with different load (using ANN- I & II).

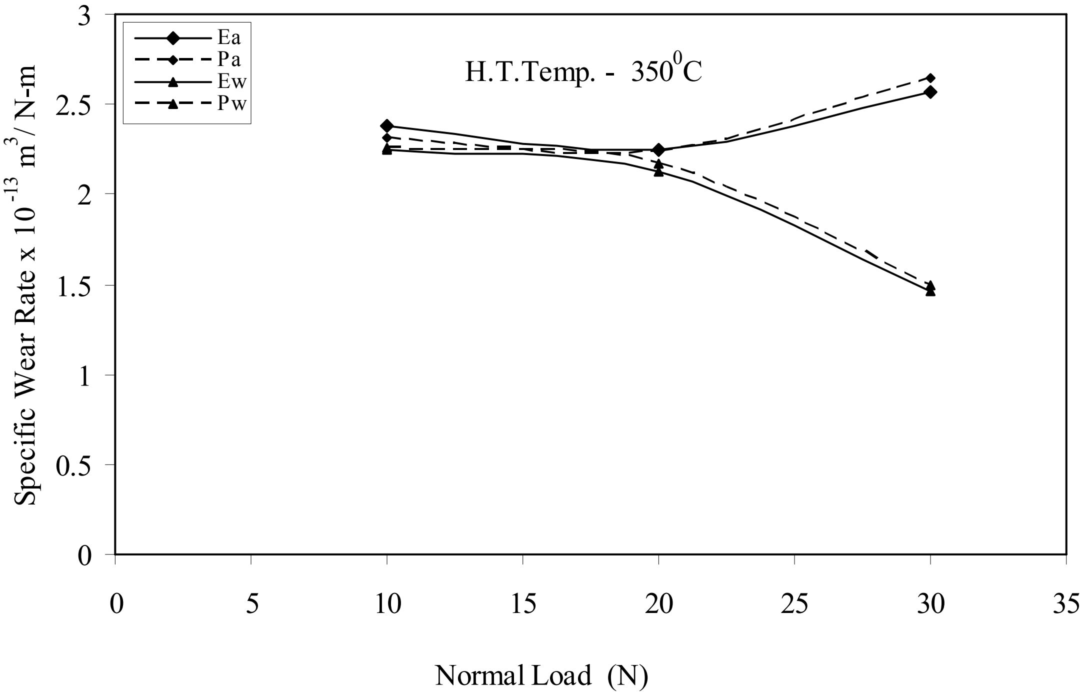


Fig. 5.6 (a)

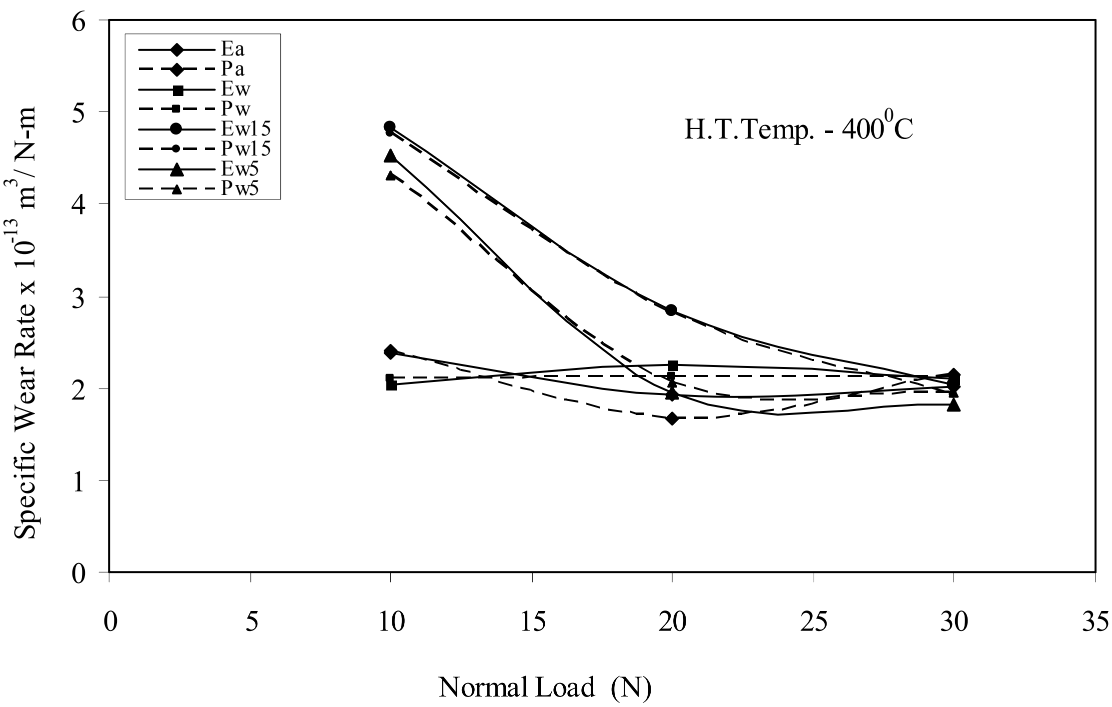


Fig. 5.6 (b)

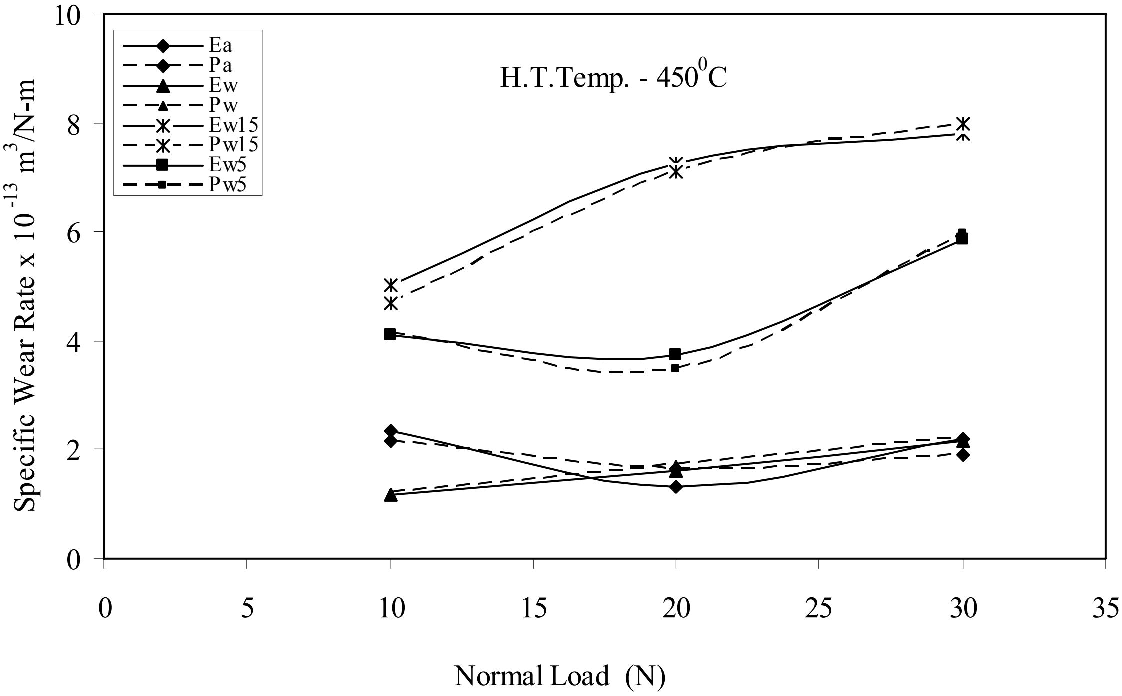


Fig. 5.6 (c)

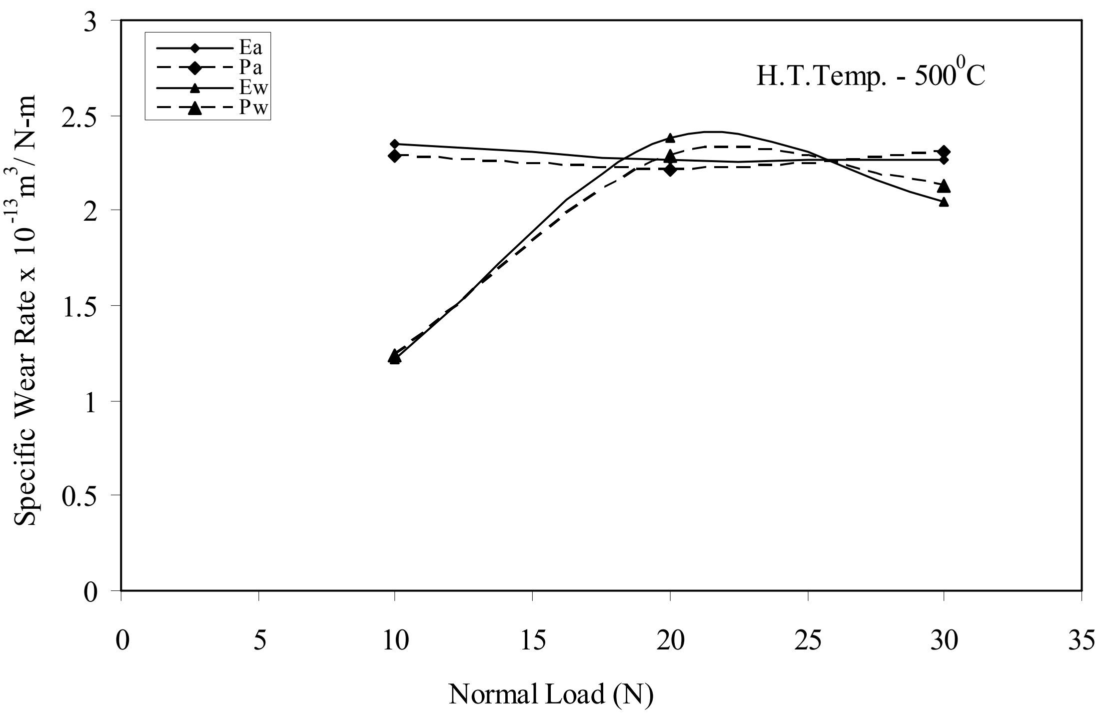


Fig. 5.6 (d)

Figs.5.6 (a-d) Comparison between experimental and predicted values of specific wear rate with different load (using ANN- I & II).

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CHAPTER - 6

CONCLUSIONS

The conclusions drawn from the present investigation are as follows:

- Red mud, the waste generated from alumina plant can be successfully used as a reinforcing material to produce Metal-Matrix Composite (MMC) component in aluminium matrix to be used in wear environment. It can be successfully used in place of conventional aluminium intensive material, there by a saving of about 15 percent matrix material could be achieved.

- There is good dispersibility of red mud particles in aluminium matrix which improves the hardness of the matrix material and also the wear behaviour of the composite. The effect is increase in interfacial area between the matrix material and the red mud particles leading to increase in strength appreciably.

- The specific wear rate of the composite decreases with addition of filler volume fraction, and after attaining a minimum value (15-20%) it again increases. Thus there exists an optimum filler volume fraction which gives maximum wear resistance to the composite.

- Many parameters e.g. sliding velocity, sliding distance and load are responsible for wear. However it is more appropriate to express the sliding wear results in terms of wear co-efficient (K), extracted from Archard's law. Wear Co-efficient (K) is a Co-relation factor between several variables of the sliding wear experimental results. For the present case it is found that wear co-efficient tends to decrease with increasing particles volume contact (15-20%), which confirms that red mud addition is beneficial in reducing the wear of aluminium red mud composite.

- The results indicate that quenching of heat treated samples in water gives better wear resistance than that achieved by air cooling. This is due to higher cooling rates attained in water quenching which induces more strain in the samples when compared to those induced by air cooling.

- The heat treatment temperatures concerned are low. So the occurrence of chemical reaction between the phases present is approximately nil. However, there is the chance of mutual dissolution among the phases present and the phases formed to increase the wear resistance by heat treatment.

- It appears from this study that the oxide phases like Al_2O_3, Fe_2O_3, TiO_2 etc. might have dispersed uniformly through out in the aluminium matrix thus strengthening the resulting (heat treated) composite.

- It has been observed that the debris formed during sliding wear is mainly consist of iron oxide (Fe_2O_3). Crack formation, propagation and alignment of hard particles (red mud) are the consequence of the operating mechanisms. When a sample is quenched; although the grain size of aluminium remains smaller but heating at 450^0C has generated grain growth and matrix hardening. So with increased applied load debris which is formed might have pressed on the surface there by reducing the material loss in the samples.

- The wear properties of the composite depends on many factors, such as sliding velocity, filler volume fraction, sliding distance and load. Computation through neural networks is one of the recently growing areas of artificial intelligence. Neural networks are promising due to their ability to learn highly non-liner relationship. It can also be gainfully employed to simulate property-parameters co-relationship in a space larger than the experimental domain. It is evident from the present study that the artificial neural technique has the potential to predict and analyze the wear behaviour of metal matrix composites if it is properly trained.

Recommendation for Further Research

- In this study red mud particles of 150 microns have been used. This can further be extended to other particle sizes to study the effect of particle size on wear behaviour of the composite.

- Since the heat treated samples with different quenching media are showing good wear resistant properties, the work can be further extended to other quenching media like brine solution, oil quenching etc. The heat treatment temperatures of 400^0 C to 450^0 C are showing better wear resistance values. Therefore, at these temperatures the soaking time can be increased and further the wear properties can be evaluated.

- The present investigation is limited to sand casting only. However other available casting techniques could be tried and analyzed so that a final conclusion can be drawn there from. However the results provided in this thesis can act as a base for the utilization of this industrial waste to prepare a composite to be used in wear environment.

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References

1 A.K.Dhingra, "metal replacement by composite", *JOM* 1986, Vol 38 (03), p. 17.

2 K.Upadhya, "composite materials for aerospace applications, developments in ceramic and metal matrix composites", Kamaleshwar Upadhya, ed.., warrendale, PA: TMS publications, 1992, pp. 3-24.

3 Greg Fisher, "Composite: Engineering the ultimate material", Am. Ceram. Soc, Bull. Vol. 63 (2), pp. 360-364.

4 T.G.Nieh, K.R. Forbes, T.C. Chou and J. Wadsworth, "Microstructure and deformation properties of an Al_2O_3-Ni_3Al composite from room temp to 1400^0C", High performance Composites for the 1990's Eds. S. K. Das, C. P. Ballard and F. Marikar, TMS-New Jersey, 1990, pp 85-96.

5 T. W. Clyne, An Introductory Overview of MMC System, Types and Developments, in Comprehensive Composite Materials, Vol-3; Metal Matrix Composites, T. W. Clyne (ed), Elsevier, 2000, pp.1-26.

6 L.M.Manocha & A.R. Bunsell "Advances in composite materials", Pergamon Press, Oxford, 1980, Vol.2, p 1233-1240.

7 Jartiz, A.E., Design 1965, pp. 18.

8 Kelly, A. (1967) Sci. American 217, (B), 161.

9 Berghezan, A. Nucleus, 8(5), 1966, (Nucleus A. Editeur, 1, rhe, Chalgrin, Paris, 16(e).

10 Van suchetclan, Philips Res. Repts. Vol. 27. 1972, pp. 28.

11 B.D.Agarwal and L.J.Broutman, “Analysis and performance of fiber composites” John Wiley & Sons, New York, 1980, pp.3-12.

12 J.O.Outwater, The Mechanics of Plastics Reinforcement Tension, Mod. Plast: March 1956.

13 R.Wetter, Kunststoffe in der Luft-und Raumfahrt, Kunststoffe, 60, Heft 10 (1970).

14 P.H.Selden, ‘ Glasfaserverstarkte Kunststoffe’, SpringerVerlag, 1967.

15 Pradeep Rohatgi, IUNIDO’s State-of-the-art series: “Advances in Materials Technology: MONITOR”, Compiled by the Industrial Technology Development Division Department of Industrial Promotion, Vienna, Austria, No.17, Feb. 1990.

16 N.J. Parrat, “Reinforcement effects of Silicon Nitride in Silver and Resin Matrices”, Powder Metallurgy, Vol. 7(14), 1964, pp 152-167.

17 R. R. Irving, “Composites Go After Commercial Markets”, Iron Age, Sept.5th, 1986, pp 35-38.

18 A. Mortensen, J.A. Cornie and M. C. Flemings, “Solidification processing of Metal Matrix Composites”, JOM, Vol. 40(2), 1988, pp 12-19.

19 D.L. McDanels and C.A. Hoffman, “Microstructure and orientation effects on properties of discontinuous Silicon Carbide/ Aluminum Composites” NASA Tech. Pap. 2303, Cleveland, OH, 1984, pp 1-29.

20 J.L. Cook and Walter R. Mohan, “Whisker-reinforced MMCs’ Metal, Carbon / Graphite and Ceramic Matrix Composites”, 1987, pp 896-902.

21 Milton W. Toaz, “Discontinuous Ceramic Fiber MMCs” International Encyclopedia of Composites, Vol. 3. ed. Stuart M. Lee, VCH Publishers, NY, p. 903-910.

22 D. L. McDanels and A. R. Signorelli, “Evaluation of low cost Aluminum Composites for Aircraft engine Structural Applications”, NASA Tech. Memo. No. 83357, Washington, DC, 1983.

23 William J. Baxter, “The strength of MMCs Reinforced with Randomly oriented Discontinuous Fibers”, Mett. Tran. Vol. 23A, Nov. 1992, pp 3045-3053.

24 David M. Schuster, Michael D. Skibo and Williams R. Hoover, “Production and Semi-Fabrication of an Aluminum Composite Material”, Light Metal Age, Feb. 1989, pp 15-19.

25 H. J. Rack, “P/M Aluminium MMCs’ Dispersion Strengthened Al Alloys”, eds. Y.M. Kim and W. M.Griffith, TMS, Warrandale, PA, The Metallurgical Soc., 1988, pp 15-19.

26 Alan L, Geiger and J.Andrew walker, “The processing and properties of discontinuously reinforced Aluminium Composite”, JOM, August 1991, pp 8-15.

27 R.L. Trumper, Met. Mater, Vol. 3, 1987, p p. 662.

28 R. A. Higgins, “Properties of Engg. Materials”, Holder & Stoughton , 1986.

29 Margaret Hunt, “Aerospace Composites”, Mater. Engg., Cleveland, Vol. 108(6), 1991, pp 27-30.

30 J. Lock; Prof. Engg. , April 1990, Vol. (21).

31 K. U. Kainer. Prasad. “Composite material Technology”, Vol. 37, 1991, pp.191.

32 W. Wei, “High Temp. MMCs for Aero Engines; Challenges and potential”, Metals and Materials Journal, Aug 1992, pp 430-435.

33 Richards Demeis, “New life for Aluminium”, Aerospace America, March1989, pp. 26-29.

34 M. Taya & R.J.Arsenault, “Metal Matrix Composite thermo mechanical behavior”, Pergamon press, 1989.

35 J. Doychak, “Metal and Intermetallic Matrix Composites for Aerospace Propulsion and Power Systems”, JOM, Vol. 44(6), 1992, pp. 46-51.

36 D.J. Lioyd, “Particle Reinforced Al and Mg Matrix Composites”, Int. Mat. Rev., Vol. 39(1), 1994, pp. 1-23.

37 “Advances in Materials Technology Monitor”, Butter Worth, London, 1995, pp 68.

38 Kirit. J. Bhansali and Robert Mehrabian, “Abrasive wear of Aluminium-Matrix Composites”, Journal of Metals, September 1982, pp 30-34.

39 A.G. Wang and I.M.Hutchings, “Wear of Alumina Fiber-Aluminium Metal Matrix Composites by two body abrasion”, Mater. of Science and Tech., January 1989, Vol 5, pp 71-75.

40 V. Constantin, L.Scheed et al., Journal of Tribology Trans., ASME, 788/ Vol. 121, Oct 1999.

41 A.Wang & H.J.Rack, “Transition wear behaviour of SiC-particulate and SiC-whisker reinforced 7091 Al metal matrix composites”, Journal of Material Science and Engineering A, Vol. 147, 1991, pp 211-224.

42 T.Alpas, J.Zhang, “Effect of microstructure (particulate size and volume fraction) and counter face material on the sliding wear resistance of particulate-reinforced aluminum matrix composites”, Metall. Mater.Trans. A, Vol. 25, 1994, pp 969-983.

43 Rohatgi. P.K., Guo. R.Q., Huang. P., Ray .S., “Friction and Abrasion Resistance of Cast Aluminum Alloy- Flyash Composites”, Metal. Mater. Trans. A, Vol. 28A, 1997, pp. 245-250.

44 A.P. Sannino, H.J.Rack, “Dry sliding wear of discontinuously reinforced aluminum composite: review and discussion”, Wear, Vol.189, 1995, pp 1-19.

45 M.K.Surappa, S.V.Prasad, P.K.Rohatgi, “Wear and abrasion of cast Al-alumina particle composites”, Wear Vol. 77, 1982, pp 295-302.

46 A.Wang, H.J.Rack,“Dry sliding wear in 2124 Al-SiCw/17-4 PH stainless steel systems”, Wear Vol. 147, 1991, pp 355-374.

47 Mechmet Acilar, Ferhat Gul “Effect of applied load, sliding distance and oxidation on the dry sliding wear behaviour of Al-10 Si/C_p composites produced by vacuum infilatration techniques. Journal of Materials & Design Vol.25, (2004) pp 209-217.

48 Liu Yao-hui, Du Jun et.al. “High temperature friction and Wear behaviour of Al_2O_3 and /or Carbon short fibre reinforced Al-12 Si alloy Composites” Wear 256, 2004, pp 275-285.

49 M.Bai, Q.Xue, X.Wang, Y.Wan, W.Liu, “Wear mechanism of SiC whisker-reinforced 2024aluminum alloy matrix composites in oscillating sliding wear tests”, Wear Vol. 185 ,1995, pp 197-202.

50 A.Alahelisten, F.Bergman, M.Olsson, S.Hogmark, “on the wear of aluminum and magnesium metal matrix composites”, Wear Vol.165, 1993, pp221-226.

51 J.Q.Jiang, R.S.Tan, A.B.Ma, “Dry sliding wear behaviour of Al_2O_3-Al composite produced by centrifugal force infiltration”, Material Science and Technology, Vol. 12, 1996, pp 483-488.

52 P.N.Bindhumadhan, H.K.Wah, O.Prabhakar, “Dual particle size (DPS) composites: effect on wear and mechanical properties of particulate matrix composites” Wear, Vol. 248, 2001, pp 112-120.

53 S.C. Tjong, S.Q. Wu, and H. Liao:“Wear behavior of an Al–12% Si alloy reinforced with a low volume fraction of SiC particles.” Journal of composite science and technology, Vol–57, Issue–12, Dec 1997, pp 1551-1558.

54 S.C.Tjong, H.Z.Wang and S.Q.Wu “Wear Behavior of Aluminum based Metal Matrix Composites Reinforced with a Perform of Aluminosilicate Fiber” Metallurgical and Materials Transactions A, Vol 27A, (1996) 2385-2389.

55 M.Singh, D.P.Mondal et.al. “Development of light weight aluminum alloy hard particle composite using natural minerals for wear resistance application. National conventions on Emerging materials on wear applications. paper no TS- 4/5, 2003, Bhopal.

56 Dry sliding Wear behaviour of Cast SiC reinforced Al MMCs.Tiejuna Ma, Hideki Yamaura et.al. Material Science Engineering, A, 360 (2003) pp 116-125.

57 C.Samuel Weaver, D Richard Nixdorf and Gerald Vaughan, 'Sic Whiskers and Platelets,'Ceram.Trans.James D.Cawley, ed., The Am.Ceram.Soc. Inc, Westerville, Ohio, Vol.2, 1987, pp 397-406.

58 R.S.Thakur & S.N.Das;"Red mud Analysis & Utilization", published by NISCOM and Wiley Eastern Ltd., New Delhi, 1994.

59 Hermann E., Chem. Ztg., 1937; 61, 493-6, Chem.Abstr.1937, 31, 5955.

60 Charrin V., Genie Civil 1954, 131, 332-4, Chem.Abstr. 1955, 49, 539g.

61 Ferdinand A.A. & Gregoire R.R., Fr1, 157, 477 May 29, 1958, Chem. Abstr. 1960, 54, 19430e.

62 Elmer P., Freiberger Forschungsh, B67 117 – 30 (1962); Chem. Abstr. 1962, 57, 12166a.

63 Thakur R.S. & Sant B.R., J.Sc.Ind.Res.1974; 33(8), 408-16, Chem. Abstr. 1975, 82, 159934x.

64 Harvath G. & Illyes J., Banyasz Kohasz Lopak, Kohasz (1975); Chem. Abstr. 1975, 83, 196543k.

65 Thakur R.S, Muralidhar J. & Sant B.R., Chem Age of India, 1977, 28(2), pp39-40.

66 Aggarwal P.S, Lele R.V. & Sen. S.K., Chem Age of India 1977; 28(2), pp.114-115,Chem.Abstr.1977, 86,175729x.

67 Grigoreva .D., Volfson G.I., Malts N.S. & Shmorgunenko N.S., Tsvetn.Met, 1977;(7) 34-5, Chem. Abstr. 1977, 87, 155285s.

68 Kudinov B.Z., Bychin A.I., Leontev L.I., Kiselev V.A. & Drug_alev S.M., Deposited Doc. VINITI 1306-77, 1977, p 11 Chem.abstr.1979, 90, 74885x.

69 Pustilnik G.L., “Komplekon. Ispolz. Syrevykh Resur Predpr. Tsvetn. Metall” 1974, Pub 1977 248-74: Edited by Adbekyan A.kh. Isz’ Aiastin’ Yerevan; Chem.Abstr. 1979, 91, 195223j.

70 Zamb J., Trav.Com . Int. Etude Bauxites Alumine Alum, 1979; 15, pp.265-277,Chem.Abstr. 1980, 93, 117887f .

71 Nikolaev, I. V. TsvetnMet 1983; (6) 61-3, Chem. Abstr.1983, 99,73009p.

72 Stanescu N., MinePet.Gaze.1990, 41(5) 222-4; Chem.Abstr.1991, 114,86023s.

73 R. Mehrabian, R.G. Riek and M. C. Flemings, “preparation and casting of Metal-Particulate Non-Metal Composites,” Metall. Trans, Vol. 5A, 1974, pp 1899-1905.

74 J. Eliasson and R. Sandstorm, “Applications of Aluminium Matrix Composites,” Part 1, G. M. Newaz, H. Neber-Aeschbacherand F. H. Wohlbier eds., Trans. Tech. publications, Switzerland, 1995, pp 3-36.

75 John E. Allison, Gerald S. Cole, “Metal Matrix Composites on the automotive Industry: Opportunities and Challenges”, JOM, Vol. 45(1), 1993, pp 19-24.

76 D. J. Lloyd, “Particulate Reinforced Composites Produced by Molten mixing,” High Performance Composites for the 1990’s, eds. S.K.Das, C.P. Ballard and F.Marikar, TMS-New Jersey, 1990, pp 33-46.

77 M.G. McKimpson and T.E.Scott, “Processing and Properties of MMCs Containing Discontinuous Reinforcement”, Mat. Sci. and Engg., Vol. 107A, 1989, pp 93-106.

78 H.J. Rack, “Metal Matrix Composites”, Adv. Mater. Processes, Vol. 137 (1), 1990, pp 37-39.

79 A. W. Urquhart, “Molten Metals Sire MMCs, CMCs”, Adv. Mater. Processes, Vol. 140(7), 1991, pp 25-29.

80 V. V. Bhanuprasad, K. S. Prasad, A.K. Kuruvilla, A. B. Pandey, B. V. R. Bhat and Y. R. Mahajan, “Composite Strengthening in 6061 and Al-4Mg Alloys”, . at. Sci. Vol. 26, 1991, pp 460-466.

81 M. S. Zedias, P. S. Gilman and S.K.Das, “High Temperature Discontinuously Reinforced Aluminium”, JOM, Vol. 43(8), 1991, pp 29-31.

82 M. S. Zedias, P. S. Gilman and S.K.Das, “ High Temperature Aluminium-Base Composites”, High performance Composites for the 1990’s eds. S. K. Das, C.P.Ballard and F. Marikar, Tms-Newjersey, 1990, pp 61-82.

83 C.P. You, A.W. Thompson and I. M. Bernstein, “Proposed Failure Mechanism in a Discontinuously Reinforced Aluminium Alloy”, Scr. Metall., Vol. 21, 1987, pp 181-185.

84 T. W. Clyne and J. F. Mason, “ the squeeze Infiltration process for Fabrication of MMCs”, Metall. Trans., Vol. 18A, 1987, pp 1519-1530.

85 M. Gupta, I.A. Ibrahim, F. A. Mohamed, E. J. lavernia, “Wetting and Interfacial Reactions in Al-Li-SiCp MMCs Processed by spray Atomozation and Deposition”, J. Mat. Sci. Vol. 26, 1991, pp 6673-6684.

86 D.Z. Yang, S. L. Dong, J. F. Mao and Y. X. Cui, "Fabrication Microstructure and Properties of A SiCw/ Al-Li-Cu-Mg-Zr Composite", Key Engineering Materials, Vol.s 104-107, Metal Matrix Composites, Part 1, G. M. Newaz, H. Neber-Aeschbacher and F. H. Wohlber eds., Trans. Tech. Publications, Switzerland, 1995, pp 627-632.

87 D.J. Lloyd, "The Solidification Microstructure of Particulate Reinforced Al/SiC Composites", Comp. Sci. Tech., Vol. 35, 1989, pp 159-179.

88 D Charles, "Addressing the Challenges of Aircraft Components design and Manufacturing from MMCs", J. Aerospace Engg (Proc. I. Mech E) pp 1-13, 1992.

89 Michael E. Buck, "Addressing fibers from Advanced Composites", Advanced Materials and Processes, pp 61-68, Sept 1987.

90 Alan, L.Geigr and Michael Jackson, "Low-Expansion MMCs Boost Avionics", Advanced Materials and Processes", pp 23-32, July 1989.

91 J. R. Roos, J. P. Celis, J. Franser and C.Buelens, "the Development of Composite Plating for Advanced Materials", JOM, Vol. 42(11), 1990, pp 60-63.

92 Herbert Dietrich, "Carbon/Carbon, Protected / Protedted", Mater. Engg. Vol. 108(8), 1991, pp 34-35.

93 T.S. Chester, "Non-metallic Materials for Gas Turbine Engines: Are They Real?". Adv. Mater. Processes, Vol. 139(6), 1991, pp 32-39.

94 M.V. Roode, J. R. Price and C. Stala, "Ceramic Oxide Coatings for the Corrosion Protection of SiC", J. Engg. Gas Turbines Power Trans. ASME, Vol. 115(1), 1993, pp 139-149.

95 D. Huda, M.A. El Baradie & M.J.S. Hashmi, “Metal Matrix Composites: Materials aspects. Part II” journal of material processing technology, Vol.37 (1993),528-541.

96 Alok Satapathy & S.C.Mishra “Plasma Spray Coating of Red Mud on Metal” Proceeding of DAE-BRNS, International Symposium on Applications of Power Beams in Advanced Material Processing, BARC, Mumbai, 2002, pp.709-712.

97 E. Hunt, P.D. Pitcher and P. J. Gregson, “Advanced Al and Mg Alloys”, T. Khan and G. Effenberg eds., ASM.

98 D. H. Kim, E.J. Lavernia and J. C. Earthman, “ Fatigue Crack growth behaviour of a continuous alumina fiber reinforced Magnesium alloy”, High performance Composites for the 1990’s eds. S.K. Das, C. P. Ballard and F. Marikar, TMS-New Jersey, 1990, pp 117-126.

99 P.J. Meachter and J.E. Oneil, “Communication: Rapid Solidification Processing of Magnesium-Lithium Alloys”, Metall. Trans., Vol. 15A, 1984, pp 237-240.

100 J.E. Hack, R. E. Page and G.R. Leverant, “Tensile and Fatigue Behaviour of Aluminium Oxide Fiber Reinforced Magnesium Composites: part I. Fiber Fraction and Orientation” , Metall. Trans., Vol. 15A, 1984, pp 1389-1396.

101 N.Eustathopoulos, D.Chatain and L.Coudurier, “Wetting and Interfacial Chemistry in Liquid Metal Ceramic Systems”, Mat.Sci and Engg. Vol.135A, 1991, pp 83-88.

102 R.J.Arsenault, ‘The Strengthening of Al Alloy 6061 by Fiber and Platelet Silicon Carbide,’ Mat. Sci. Engg., Vol. 64, 1984, pp171-181.

103 I.Adeqoyin, F.A.Mohamed and E.J.Lavernia, ‘Particulate Reinforced MMCs-A Review, J. Mat Sci., Vol.26, 1991, pp1137-1156.

104 Von F. Lowshenko, F. Kunter and G.Jangg, "Eigenschaften Von Dispersion geharteten Al-Al_4C_3 Werkstoffen", Planseeberichtefur Pulvemattallurgie, Bd. Vol.25, 1997, pp. 205-213.

105 R. Tiwari, H. Herman, K. Kowalsky and D.R. Marantz, "Mechanical behaviour of thermal sprayed Metal-Matrix Composites", High Performance Composites for the 1990's, eds. S.K.Das, C.P. Ballard and F. Marikar, TMS-New Jersey, 1990, p 195.

106 A.H. Nakagawa and M.N.Gungor, "Microstructure and Tensile properties of $A_{l2}O_3$ Particle Reinforced 6061 Al Cast Composites", eds. P.K.Liaw and M.N.Gungor, "Fundamental Relationship Between Microstructure and Mechanical Properties of MMCs", The Minerals, Metals & Materials Society, 1990, pp 127-143.

107 A. K. Kuruvilla, V.V. Bhanuprasad, K. S. Prasad and Y.R. Mahajan, "Effect of different reinforcements on Composite-strengthening in aluminium", Bull. Mater. Sci., Vol. 12(5), 1989, pp 495-505.

108 R.L. Mehan, "Fabrication and Evaluation of Sapphire Reinforced Al Composites", Metal Matrix Composites, ASTM-STP, Vol. 438, 1968, pp 29-58.

109 J. Zhang, R.J. Perez, M. N. Gungor and E.J.Lavernia, "Damping Characteristics of Graphite Particulate Reinforced Aluminium Composites", Developments in Ceramics and Metal Matrix Composites. Kamleshwar Upadhya, ed., Warrendale, PA: TMS Publication, 1992, pp 203-217.

110 Thomas D. Nixon and James D.Cawley,"Oxidation Inhibition Mechanisms in coated Carbon-Carbon Composites", J. Am. Ceram. Soc., Vol. 75(3), 1992, pp 703-708.

111 M.V Ravichandran. R.Krishna Prasad and E.S.Dwarakadasa, J. Mater. Sci. Letts; Vol-11, 1992, p.452.

112 P.K.Balasubramanian, P.Srinivasa Rao, et.al. J.Mater.Sci.Letts., Vol-8, 1989, p.799.

113 J.Singh, S.K.Goel, V.N.S.Mathur and M.L.Kapoor; J.Mater. Sci., Vol-26. 1991.

114 Deonath and P.K.Rohatgi, ‘Fluidity of Mica Particle Dispersed Aluminum Alloy: J. Mat. Sci., Vol. 15, 1980. pp 2777-2784.

115 Deonath, R.T.Bhat and P.K.Rohatgi, “Preparation of Cast ALLOY-Mica Particle Composites”: J. Mater. Sci., Vol. 15, 1980, pp.1241-1251.

116 M.K.Surappa and P.K.Rohatgi, ‘Preparation and Properties of Cast Aluminum Ceramic Particle Composites, ‘J.Mat. Sci., Vol.16, 1981, pp.983-993.

117 A.Banerji, M.K.Surappa and P.K.Rohargi, Cast Aluminum Alloys Containing Dispersions of Zircon Particle, ‘Metall. Trans. Vol. 14B, 1983, PP.273-283.

118 M.S.Zedalis, J.D.Bryant, P.S.Gilman and S.K.Das, ‘High-Temperature Discontinuously Reinforced Aluminium. JOM, Vol.43 (8), 1991. pp. 29-31.

119 M.Taya and R.J.Arsenault “Metal Matrix Composites–Thermo mechanical behaviour” (1989) New York, Pergmon Press, p -238-243.

120 K.K.Chawla, Composite materials–Science and Engineering, (1987) New York Springer Verlag, pp. 67-72.

121 D.Huda, M.A.Elbardie& M.S.J.Hashmi, Jour. Mat. Proc. Tech., Vol.37, 1993, pp.529- 530.

122 J.R.Vinson & T.W.Chou, “Composite Materials and their use in Structure”, Applied Science publisher, 1975, p 44.

123 N. Axen, A.Alahelisten and S.Jacobson"Abrasive wear of alumina fibre reinforced aluminum." Journal of wear Vol.173, Issue 1-2, 1994, pp.95–104.

124 Zongyi.Ma, Jing, Yuxiong. Lu, Hongwei.Shu, and Inurn. Gao. "Abrasive wear of discontinuous SiC Reinforced aluminum alloy composites". Journal of wear Vol. 148, Issue-2, Aug 1991.pp. 287 – 293.

125 K.M. Shorowordi, A.S.M.A. Haseeb, J.P.Ceils,"Velocity Effect on Wear, Friction and Tribochemistry of Aluminum MMC sliding against Phenolic Brake Pad ". Journal of wear, 2003.

126 Yoshiro.Iwai, Hidetomo.Yonede, and Tomomi.Honda "Sliding wear behaviour of SiC whisker reinforced aluminum composite". Journal of wear, Vol. 181-183, Issue –2, Mar 1995, pp 594-602.

127 Liang.Y.N, Ma.Z.Y, Li.S, Bi.J "Effect of particle size on wear behaviour of SiC particulate reinforced aluminum alloy composite" Journal of Material science, Vol- 14, Jan 1995, pg 114-116.

128 L.Cao, Y.Wang, C.K.Yao: "The wear properties of an SiC whisker reinforced aluminum composite". Journal of wear, Vol. 140, Issue-2, Nov 1990, pp. 273-277.

129 A. Ravikiran, M.K.Surappa "Effect of sliding speed on wear behaviour of A 356 Al –30 wt% SiCp MMC", wear, Vol 206 ,1997 pp. 33-38.

130 F.A.Girot, J.M.Quenisset & R.Naslain, Composite Science Technology, Vol.30, 1987, p. 155.

131 F.A. Badia and P.K. Rohatgi, AFS Trans. Vol 77, 1969, p. 402.

132 F.A. Badia, D.F. Macdonald and J.R. Pearson, AFS Trans., (1971) 265.

133 A.M. Patton, J. Inst. Met., Vol. 100 (1972) 197.

134 B.C. Pai and P.K. Rohatgi, J. Mater. Sci., Vol. 13 (1978) 329.

135 M. Suwa, K. Komaro and K. Sueno, Jpn. Soc. Lubr. Eng., Vol. 40 (1986) 1074.

136 V. Agarwala and D. Dixit, Trans. Jpn. Inst. Met., Vol. 8 (1981) 521.

137 B.P.Krishnan, M.K.Surappa and P.K.Rohatgi, J. Mater. Sci., Vol.16, 1981, p.1209.'

138 P.R. Gibson, A.J. Clegg and A.A. Das, Foundr. Trade J., Vol. 152, 1982, pp. 253.

139 D. Huda, M.A.El Baradie, & M.J.S.Hashmi, "Metal Matrix Composites: Manufacturing aspects. Part I", journal of material processing technology, Vol. 37, 1993, pp. 513-528.

140 M. A. EL Baradie, "Manufacturing aspects of metal matrix composites", Journal of Materials Processing Technology, Vol. 24, 1990, pp 261-272.

141 S.D. Ridder, S.Kou and R.Mehrabian, "Effect of Fluid Flow on Macrosegation in Axi-Symmetric Ingots," Metall. Trans., Vol. 12B, Sept.1981, pp 435-447.

142 R.H. Bricknell, "The Structure and Properties of A Nickel-Base Super alloy Produced by Osprey Atomization-Deposition", Metall. Trans., Vol. 17A, 1986, pp 583-591.

143 S. Kohara, Mater. Manufact. Process., Vol. 5, 1990, p. 51.

144 A.R. Champion, W.H. Krueger, H.S. Hartman and A.K. Dhingra, Proc. Int. Conf. on Composite Materials, AIME, Warrendale, PA 1978, p. 883.

145 D.L. Danels, “Analysis of Stress-Strain, Fracture and Ductility Behaviour of Aluminium Matrix Composites Containing Discontinuous Silicon Carbide Reinforcement”, Metall. Trans., Vol. 16A, 1985, pp 1105-1115.

146 M.G. McKimpson, E.L. Pohlenz and S.R. Thompson, “Evaluating the Mechanical Properties of Commercial DRA”, JOM, Vol.45 (1), 1993, pp 26-29.

147 Z. Zhao, Z. Song and Y. Xu, “Effect of Microstructure on the Mechanical Properties of an Al Alloy 6061-SiC Particle Composite”, Mater. Sci. Engg., Vol. A132 (1-2), 1991, pp 83-88.

148 Margaret Hunt, “Form and Function in MMCs”, Mater. Engg., Vol. 107(6), 1990, pp 27-30.

149 M.K. Jain, V. V. Bhanu Prasad, S.V. Kamat, A. B. Pandey, V. K. Varma, B. V. R. Bhat and Y. R. Mahajan, “Processing Microstructure and properties of 2124 Al-SiCp Composites”, Int. J Pow. Met., Vol. 29(3), 1993, pp 267-275.

150 M. Taya, K.E.Lulay and D.J.Lloyd, “Strengthening of a Particulate Metal Matrix Composite by Quenching”, Acta Metall., Vol. 39, 1991, pp 73-87.

151 P.M. Kelly, “The Quantitative Relationship Between Microstructure and properties in Two-Phase Alloys”, Int. Met. Rev., Vol. 18, 1973, pp 31-36.

152 T.G.Nieh and D.J.Chellman, ‘Modulus Measurements in Discontinuous Reinforced Al Composites.’ Scr. Metall., Vol. 18, 1984, pp.925-928.

153 C.M. Friend, “The effect of Matrix Properties on Reinforcement is Short Al_2O_3 Fibre-Al MMCs”, J.Mat. Sci., Vol. 22, 1987, pp 3005-3010.

154 J.J. Lewandowski, D.S.Liu and C.Liu, “Observations on the Effects of Particulate size and Superposed Pressure on Deformation of MMCs”, Scr. Metall. Vol. 25, 1991, pp 21-26.

155 J.J. Lewandowski and C.Liu, “Effects of Matrix Microstructure and Particle Distribution on fracture of an Al Metal Matrix Composite”, Mat. Sci. Engg., Vol. 107A, 1989, pp 241-255.

156 V.V.Bhanuprasad, M.A.Staley, P.Ramakrishnan and Y.R.Mahajan “ Factography of Metal Matrix Composites”, Key engineering Materials, Vols. 104-107, Metal Matrix Composites, part 2, G.M. Newaz, H. Neber-Aeschbacher and F.H. Wohlbier eds, *Trans Tech Publications*, Switzerland, 1995, pp 495-506.

157 G.L.Povirk, A. Needleman and S.R. Nutt, “An Analysis of the Effect of Residual Stresses on Deformation and Damage Mechanisms in Al-SiC Composites,” Mat. Sci. Engg. Vol. 132A, 1992, pp 31-38.

158 R.J. Arsenault, N. Shi, C.R. Feng and L. Wang, “Localized Deformation of SiC-Al Composites,” Mat.Sci. and Engg., Vol. 137A, pp 55-68.

159 David A. Woodford, ‘Critical Property Evaluation of High-Temp. Composites: A Case Study in Materials Design,’ JOM, Vol. 42(11), 1990, pp 50-55.

160 S.B. Wu and R.J. Arsenault, ‘The fracture mode in SiC-Al Composites, ‘Mat. Sci. Engg., Vol. 138A, 1991, pp 227-235

161 G. Amontons, Mem. Acad. T. , Ser. A, 1699, pp 257-282.

162 N.P.Petrov, “Friction in machines and the effect of the lubricant”, Inzh.Ah, 1893, pp 71-140, Vol. 2, 1983, pp 227-279.

163 B.Tower, “First report on friction experiments”, Proc., Inst. Mech. Eng., London, Nov. 1983, pp 632-659.

164 O.Renolds, “On the theory of lubrication and it’s application to Mr. Beauchamp Tower’s experiments”, Plilos. Trans. T. Soc. London, Vol. 177, 1886, pp. 157-234.

165 R. Holm, “The frictional force over the real area of Contact”, Wiss. Vereoff. Siemens Werken, Vol. 17 (4), 1938, pp. 38-42.

166 Peterson.M. B, “Advanced in tribo-materials I Achievements in Tribology”, Amer, Soc, Mech. Eng., Vol.1, New York, 1990, pp. 91-109.

167 D.A.Rigney, “Fundamentals of Friction and wear of materials”, American Society for Metals, Metal park, Ohio.

168 M.F.Ashby and S.C.Lim, ‘Wear-mechanism maps’, Scripta Metallurgical et Materialia, Vol.24, 1990, pp. 805-810.

169 Y. Wang, T.C. lei and C.Q. Gao, ‘Influence of isothermal hardening on the sliding wear behaviour of 52100 bearing steel’, Tribology International, 1990, Vol. 23(1), pp. 47-53.

170 L.S. Eyre, “Wear Characteristics of metals”, Tribology International, October 1976, pp. 203-212.

171 .Dowson, “Wear oh where”, International Conference on wear of Materials, Vancouver Canada, April 14-18, 1985.

172 J. Blau, “Fifty years of research on the wear of metals”, *Tribology International*, Vol. 30(5), 1997, pp. 321-331.

173 Barwell, F. T. and Strang, C. D., “Metallic Wear”, Proc. Roy. Soc. London A 212 (III), (1952), 470-477.

174 Archard J.F., “Contact Rubbing of flat Surfaces”, J. Appl, Phys 24, 1953, pp 981-988.

175 Archard J.F. and Hirst W, “The Wear of Metal Under Unlubricated Conditions”, Proc. Roy. Soc. London A , Vol. 238, 1957, pp 515-528.

176 V. Constantin, L. Scheed and J. Masounava, Journal of Tribology, Transactions of the ASME, 788/ Vol. 121, October 1999.

177 T. Miyajima, Y. Iwai., “ Effect Of Reinforcements On Sliding Wear Behaviour Of Aluminum Matrix Composites” Journal of Wear, Vol. 255, 2003, pp 606-616.

178 Hutching I.M “Tribological properties of Metal Matrix Composites”. Journal of Material Science and Technology. Vol 10, (6), 1994, pp 513 -517.

179 Manish Narayan, M.K.Surappa & B.N. Pramila Bai. “Dry sliding wear of Al alloy 2024-Al_2O_3 particle matrix composites”, wear, Vol. 181-183, 1995, pp 563-570.

180 A.Sato, R.Meharabian “ Metall transition, Vol. 73, 1976, p 443.

181 C.S.Lee,Y.H.Kim,K.S.Han,T.lim, Wear behaviour of aluminum matrix composite materials, Journal of Material Science, Vol. 27(3), 1992, pp 793-800.

182 J.K.M. Kwok, S.C.Lim, High speed tribological properties of some Al /SiCp composites.1. Friction and wear rate characteristics, compos. Sci.Technol. Vol. 59, 1999, pp 169- 188.

183 C.Diaz.J.L, et.al, Metallurgical and Material Transitions A, 1996, Vol. 27A, pp 3259-3266.

184 N.Soda, ‘Wear of some F.F.C metals during unlubricated sliding part-1. Effects of load, velocity and atmospheric pressure on wear’. Wear 33 (1975) 1-16.

185 Burwell J.T. and Strang C.D, ‘Metallic wear’, Proc.Soc (London), 212A May 1953, pp 470-477.

186 Burwell J.T., ‘Survey of possible wear mechanisms’, Wear 1, 1957/58, pp119-141.

187 K.H.Zumgahr, ‘Microstructure and wear of materials’ Elsevier, Amsterdam, 1987.

188 P.L.Ko, “Metallic wear-a review with special references to vibration-induced wear in power plant components”, Tribology International, April 1987, Vol.20, No.1, pp.66-78.

189 M.Cirino, R.B.Pipes and K.Friedrich. “The Abrasive Wear Behaviour of Continuous Fibre Polymer Composites”. Journal of Material Science, Vol 22, 1987, p. 2481.

190 A.P.Verma and P.C.Sharma, “Abrasive Wear Behaviour of GRP Composite, “The Journal of the Institute of Engineers (India) , Pt MC2,Vol.72, March 1992, p 124.

191 L.J.Yang, N.L.Loh, The wear properties of plasma transferred arc cladded satellite specimens, Surf. Coat.Technol, Vol. 71, 1995, pp. 196-200.

192 L.J.Yang, ‘Pin on disc wear testing of tungsten carbide with a new moving pin technique’ Wear, Vol. 225-229, 1999, pp. 557-562.

193 E.Rabinowicz: “Friction Wear of Materials”, Willy, New York, 1956.

194 N.L.Savchenko, P.V.Korolev, A.G.Melnikov, et.al. “Wear and Friction of transformation–toughened CMC and MMC”.Wear Vol. 249, 2002, pp-892-900.

195 M.H. Korkut, “Effect of Particulate Reinforcement on Wear Behaviour of Aluminum Matrix Composites”. Materials Science and Technology Vol.20, 2004, pp.73-81.

196 O.YLMAZ and H. TURHAN: Composites Science Technology, Vol.61, 2001, pp.2349-2359.

197 M.H.Korkut, “Microstructure and wear behavior of Al 2024\ SiFe and Al 2024\ SiFe\ Al_2O_3 composites”, Tribology International 36, 2003, pp.169-180.

198 E.HORNBOGEN and K. Friedrich, “Friction and wear of polymer composites”, Composite Materials Series, Vol.1, 1981, pp. 61-68.

199 O.YLMAZ: Material Science Technology, Vol.17, 2001, p.1285.

200 R.P.Lippmann, IEEE ASSP Mar. 4, 4 (1987).

201 D.E.Rumelhart and J.L.McCelland, Parallel Distributed Processing, Vols 1 & 2 MIT Press, Cambridge, Mass. (1986).

202 R.Hecht.Nilsen, Proc. Joint Conf. on Neural Networks, Vol. 1, 1989, pp. 593-617.

203 K. Velten, R. Reinicke, K. Friedrich, “Wear volume prediction with artificial neural networks” , *Tribology International*, Vol. 33, 2000, pp 731–736.

204 Jones, Jansen and Fusaro, “Preliminary investigation of neural network techniques to predict tribological properties”, *Tribology Transactions*, 1997, Vol. 40(2), p 312.

205 K. Genel, S.C. Kurnaz, M. Durmanb, “Modeling of tribological properties of alumina fiber reinforced zinc–aluminum composites using artificial neural network”. *Materials Science and Engineering*, Vol. A363 (2003) pp 203–210.

206 Necat Altinkok, Rasit Koker, “Modeling of the prediction of tensile and density properties in particle reinforced metal matrix composites by using neural networks”, *Materials and Design*, 2005.

207 A.Mukherjee, S.Schmauder, M.Ruhle, “Artificial Neural Network for the prediction of Mechanical Behaviour of Metal Matrix Composites”, *Acta. Metall. mater*. Vol. 43. No.11, 1995, pp 4083-4091.

208 N.Bhat and T.J.Mc.Avoy, “Use of Neural Nets for Dynamic Modeling and Control of Chemical Process Systems” Computers and Chemical Engineering Vol.14, 1990, p 573.

209 B.B.Singh and B.Mohanty, “Nom-linear Constrained Optimization using Combine Approach of Neural Network-based Modeling and SQP Optimizer.” Journal of The Institution of Engineers (India), vol.82, 2002. pt CH/2, p.46.

210 V.Rao and H.Rao, “C^{++}Neural Networks and Fuzzy Systems” BPB Publication, 2000.

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2. **Prasad Naresh & Acharya S.K**: "Sliding Wear Behaviour of Aluminium Red mud Composite." Proceedings of the 49th Congress of Indian Society of Theoretical and Applied Mechanics, Dec.27-30, 2004, pp. 51.
3. **Prasad Naresh & Acharya S.K**; "Tribological Behaviour of Aluminium Red Mud Composite." Presented at the 12th International Conference on Solid Waste Technology and Management, Philadelphia, USA, April 3-6, 2005.
4. **Prasad Naresh, & Acharya S.K**; "Wear Behaviour of Aluminium Red Mud Composite." Accepted for publication in The Journal of Institution of Engineers (India), Metallurgical and Material Science Division.
5. **Prasad Naresh, & Acharya S.K**; "Evaluation of Tribological Properties of Aluminium Red Mud Composite Using Artificial Neural Networks." Accepted for publication in The Journal of Institution of Engineers (India).
6. **Prasad Naresh & Acharya S.K**; "Dry Sliding Wear Behaviour of Aluminium Red Mud Composite for Wear Resistant Applications." Proceeding of the 43rd National Metallurgists' Day, ATM 14-16 Nov. 2005, WT-15, pp. 201.

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